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FINAL REPORT

DESIGN AND DEVELOPMENT OF AN ESTUARINE CURRENT METER

By

FOSTER H. MIDDLETON
WEN-HSIUNG LI

OFFICE OF NAVAL RESEARCH, U.S. NAVY DEPARTMENT
CONTRACT Nonr-248(37), ONR PROJECT NO. NR 083-038/7-28-52

May, 1954

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INSTITUTE FOR COOPERATIVE RESEARCH
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F. Hamburger, Jr.
C. Frank Miller
RESEARCH CONTRACT DIRECTORS

An Ultrasonic Current Meter for Estuarine Research

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AN ULTRASONIC CURRENT METER

FOR

ESTUARINE RESEARCH

GENERAL

Introduction:

The purpose of this project was to study various means for measuring the velocity of water, and to build one or more instruments that would accomplish the job according to the specifications of the contract. The two most important special specifications for this instrument were that it should operate unattended for a period of one week, and that its accuracy should be at least one per cent of full scale over the entire velocity range.

More specifically, the range of velocities of interest was from 0.08 to 5.1-feet/second, and it was desired to have readings at approximately one-half hour intervals during the one-week reading period. From these figures, some special considerations become apparent: The velocity range is quite large in that the lowest velocity of interest is only 1/64 of the highest velocity. Also, the energy requirements for such a long reading period must be kept small to minimize battery volume.

The two considerations just mentioned caused the rejection of many of the velocity sensing techniques that were given thought. The two general approaches to the problem that seemed most promising during this study program were the ultrasonic transmission method and the drag-disc method. The former method was the one adopted for a final design, and will therefore be the subject of the remainder of this report. The latter method was considered for some time, and certain difficulties caused its rejection in favor of the ultrasonic instrument. These difficulties were not sufficiently serious to justify the conclusion that the drag-disc principle cannot be applied to a practical instrument, but it was decided that effort expended on the ultrasonic meter would be more likely to result in a useful instrument in the time available. The drag-disc instrument will be discussed in Appendix A of this report.

PRINCIPLE OF OPERATION OF THE ULTRASONIC VELOCITY METER

There are two different major means of applying ultrasonic transmission techniques to the measurement of the velocity of a liquid medium. These might be called the sonar pulse system and the phase shift system. The first system would involve accurate timing of the transmission of ultrasonic pulses from one point to another in a direction parallel to the water velocity direction. In a pulse technique the most obvious source of trouble is the circuit design encountered in providing pulses with sufficiently short rise times. A companion problem would be the detection of the precise time of pulse reception. These problems could certainly be resolved, but it was concluded that the complexity of the necessary circuitry would warrant further work on the phase shift system. The literature held many suggestions for the measurement of phase difference with a high degree of accuracy with not too complicated designs. Also, several commercial phasemeters were available on the market.

A project report from the University of Michigan Engineering Research Institute entitled, "Design and Development of an Underwater Sound Velocity Meter", by Richard K. Brown, was found to be of considerable value. The work was done for the Office of Naval Research, U.S. Navy Department under Contract N6onr-23220, ONR Project No. NR 261 024.

As the title states, this contract was concerned with the design of an instrument for measuring the velocity of sound in water, while the objective here is to measure the velocity of the water. However, much of the work detailed in this report is pertinent to the Johns Hopkins project, and was of interest and very helpful.

Water Velocity Related to Phase Shift:

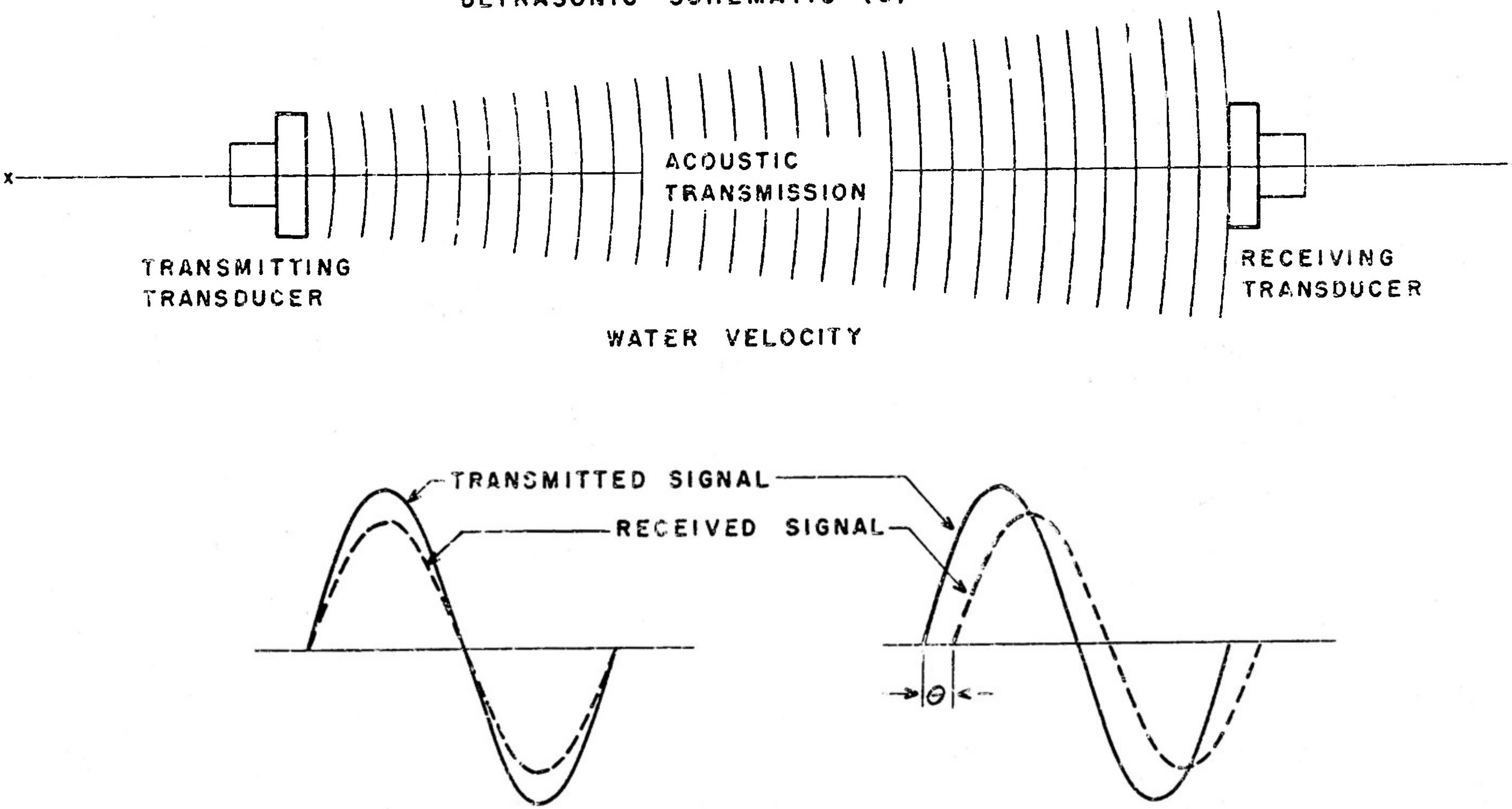
An instrument to operate on the phase shift principle might be constructed using two or more transducers capable of being aligned with the water flow direction and providing a continuous wave of acoustic energy being transmitted from one transducer to the other. The size of the transducers and the distance between them must be small in order that the velocity measured will be a "local" one, and the presence of the transducers will have no appreciable effect on the flow.

On the other hand, the transducer spacing distance is linearly related to the amount of phase shift that will be present with a given magnitude of water velocity. Since the phase shift can be increased by increasing the ultrasonic operating frequency, a basis is available for a compromise to arrive at a design that is suitably small in size, and yet has sufficient sensitivity.

A numerical example will serve to illustrate the principles involved in selecting an operating frequency and an instrument size. Reference will be made to Figure 1.

The velocity of propagation of acoustic waves in sea water is approximately 150,000 cms./second. This velocity is a function of the temperature, pressure, and the salinity of the water, but for the purpose of this example, 150,000 cms./second will serve. Suppose that the fre-

ULTRASONIC SCHEMATIC (a)



(b) ZERO WATER VELOCITY

(c) WITH WATER VELOCITY

FIG. 1

quency of the continuous wave is 100,000 cps. The resulting wavelength is 1.5 centimeters. Under these conditions the curved lines between the transducers represent pressure wave fronts progressing through the water from one transducer to the other. The speed of advance of the wave fronts is 150,000 cms./second, and the fronts are separated by 1.5-centimeter intervals. If the wave generated by the transmitting transducer is sinusoidal, then the wave at the receiving crystal will also be sinusoidal; and if the transducers are spaced an exact integral number of wavelengths apart, the two sinusoidal signals will be in phase. If the received signal is amplified to make up for losses due to the divergence of the beam and for attenuation in the water, and the two waves applied to a two-gun oscilloscope, they will appear as in Figure 1(b).

Suppose further that the transducers are spaced 100 wavelengths apart (approximately 5 feet). A change in this transducer spacing of as much as one millimeter (0.0667%) will cause a change in the original phase relationship to that shown in Figure 1(c), where $\theta = 24^{\circ}$. This amount of phase shift, which could readily be measured by commercially available phasemeters, might have been introduced in a number of different ways: (a) by changing the spacing of the transducers, (b) changing the velocity of the acoustic wave, or (c) by causing some motion of the water in the direction of the acoustic wave.

To cause the same amount of phase shift as above by means of a change in the velocity of the sound wave would require a change of one meter/second (0.0667%). A water velocity in the direction of the acoustic path of one meter/second would, of course, have the same effect.

According to the literature[1], the following are the rules that apply to the variation of the velocity of propagation of sound in sea water:

1. Velocity increases with temperature by approximately 0.2 per cent per degree Centigrade.
2. Velocity at a given depth increases with the depth by about 0.2 per cent per 100 fathoms.
3. Velocity increases very slowly with salinity, the total increase from 31 parts per 1,000 to 37 parts per 1,000 being only about 0.7 per cent or roughly 0.1 per cent for each 0.1 per cent increase of salinity.

The application of rule (1) above results in the phase shift in the example ($\theta = 24^{\circ}$) being caused by 1/3-degree Centigrade change in the water temperature. The same amount of phase shift would appear with a change of 200 feet of depth, or a change of 0.0667% of salinity.

It is apparent from the above considerations that the physical conditions of the environment are of much greater consequence than the motion of the water, as far as phase shift is concerned.

Design Considerations:

The range of velocity of water of interest to this project was stated above to be from 0.08 to 5.1 feet per second. The phase shift caused by 5.1 feet/second water velocity could instead be caused by approximately one-half degree Centigrade change in water temperature. From this standpoint,

[1] "Acoustic Measurements" by L. L. Beranek, John Wiley & Sons, Inc., page 52.

the ultrasonic approach would be highly undesirable for the measurement of water velocity since temperature changes of well over one-half degree will certainly be present under operating conditions. It was for this reason that consideration was given to the possibility of either transmitting upstream and downstream simultaneously, or sequentially. Simultaneous transmission could be accomplished by means of two acoustic paths, and would involve at least three transducers. Sequential transmission, however, could be done with one pair of transducers if commutation of the acoustic path could be accomplished. The latter system was considered to be the most promising because of its simplicity. This is therefore the most significant difference between the subject instrument and any sound velocity meter.

It was decided that any mechanical means of commutating the transducers, such as revolving the transducer assembly in the plane of the water velocity, would be extremely difficult. Therefore, it was decided to accomplish this function electrically, in a manner to be described later. This resulted in the transducer assembly being attached to the instrument housing rigidly.

Consideration was given to the subject of transducer size, spacing, and operating frequency, all of which are interrelated. The size of the transducers is of importance for two reasons: (1) the larger the transducer, the greater the undesirable effect it will have on the water flow being investigated; and (2) with a given operating frequency, a larger transducer will generate a more narrow beam which will permit more of the transmitted energy to be available at the receiver; and stray reflections, such as from the surface of the instrument housing, will be minimized.

From Viqoureux[2], the diameter of the transducer face should be approximately twelve times the operating wavelength in order that the acoustic energy be confined to a cone of 6° semi-vertical angle. Therefore, the frequency should be high so that the wavelength will be small, and the resulting transducer face diameter will be reasonable. In the case of the example, the face diameter of the transducer would be 18 centimeters with the wavelength 1.5 centimeters.

There is a practical limit to the operating frequency since the attenuation goes up with frequency. From Figure 2.22 in Beranek, the attenuation increases from 0.04 to 0.3 db/yard from 100 to 1,000 Kcps. Another reason for concern at higher operating frequencies is that the phase measurement is made more accurate after heterodyning the ultrasonic signals down to the mid-audio range. This will be discussed in more detail later. After these considerations were made, an operating frequency of one megacycle per second was selected with the thought that any higher frequency might lead to troubles because of leakage and cross-talk.

At an operating ultrasonic frequency of one megacycle per second the wavelength is one-tenth of that in the above example, namely, 0.15 centimeter. Having selected the operating frequency, it becomes necessary to consider the required phase resolution and the related acoustic path length. It was decided that, if possible, the ultrasonic path length should not exceed two feet. It was felt that having the transducers much closer than this might result in excessive disturbance to the flow field by the presence of the transducers. With this spacing and this operating frequency, there would be approximately 400 wavelengths in the acoustic path. Full scale

(2) "Ultrasonics" by P. Vigoureux, John Wiley & Sons, Inc., 1951, page 2.

water velocity would produce 0.4 wavelengths of phase shift, corresponding to approximately 145 degrees. In the case of acoustic transmission against the water velocity the phase change would be in a lagging direction, and, conversely, acoustic transmission with the water velocity would result in a leading phase change from the quiescent phase position. The total is of course 290 degrees out of a possible 360 degrees available without ambiguity.

DESCRIPTION OF ULTRASONIC METER AND ITS OPERATION

Recorder:

A surplus magnetic compass of the aircraft type was available, and it was decided to use this to obtain water velocity direction. This uses a 400-cps. inverter for excitation and a synchro repeater. An electrical signal is not therefore readily available from the compass that could be used to drive a galvanometer or some other recorder element. The simplest means of recording the repeater indication is a camera. Further, the camera seemed desirable from the standpoint that, although continuous recording was not necessary, the recording period spanned seven or eight days. A spring-driven recorder was considered, but most of these are sensitive to their orientation because of inkwells or other reasons. A study of the power requirements for the instrument programmer, the electronic circuitry, and the excitation inverter revealed that a moderate size lead-acid battery would be sufficient for the job.

As will be discussed later, the instrument can be operated either on a two or four-picture reading cycle. In either case, the readings of phase angle are taken alternately with the acoustic transmission upstream and then downstream. The four-picture reading cycle simply repeats the process and allows the checking of the readings against each other. This might be desirable in the early use of the instrument, but normally only two pictures will be taken in each reading cycle.

Suspension:

Before going into a detailed description of all of the components of the velocity meter, it might be desirable to make reference to Figure 3 which is a schematic of the arrangement of the instrument in water. The arrangement shown is one for remote operation. However, the cabling, both electrical and mechanical, is arranged in such a way that the anchor unit may be used aboard a vessel with the "fish" hanging in the water. This was done to facilitate the checkout and calibration of the instrument. The electrical cable will connect the fish and the anchor unit, and is loosely attached to the steel mooring cable. Steel cable is used between the top of the fish bridle and the lift buoy, and between the lift buoy and the surface buoy.

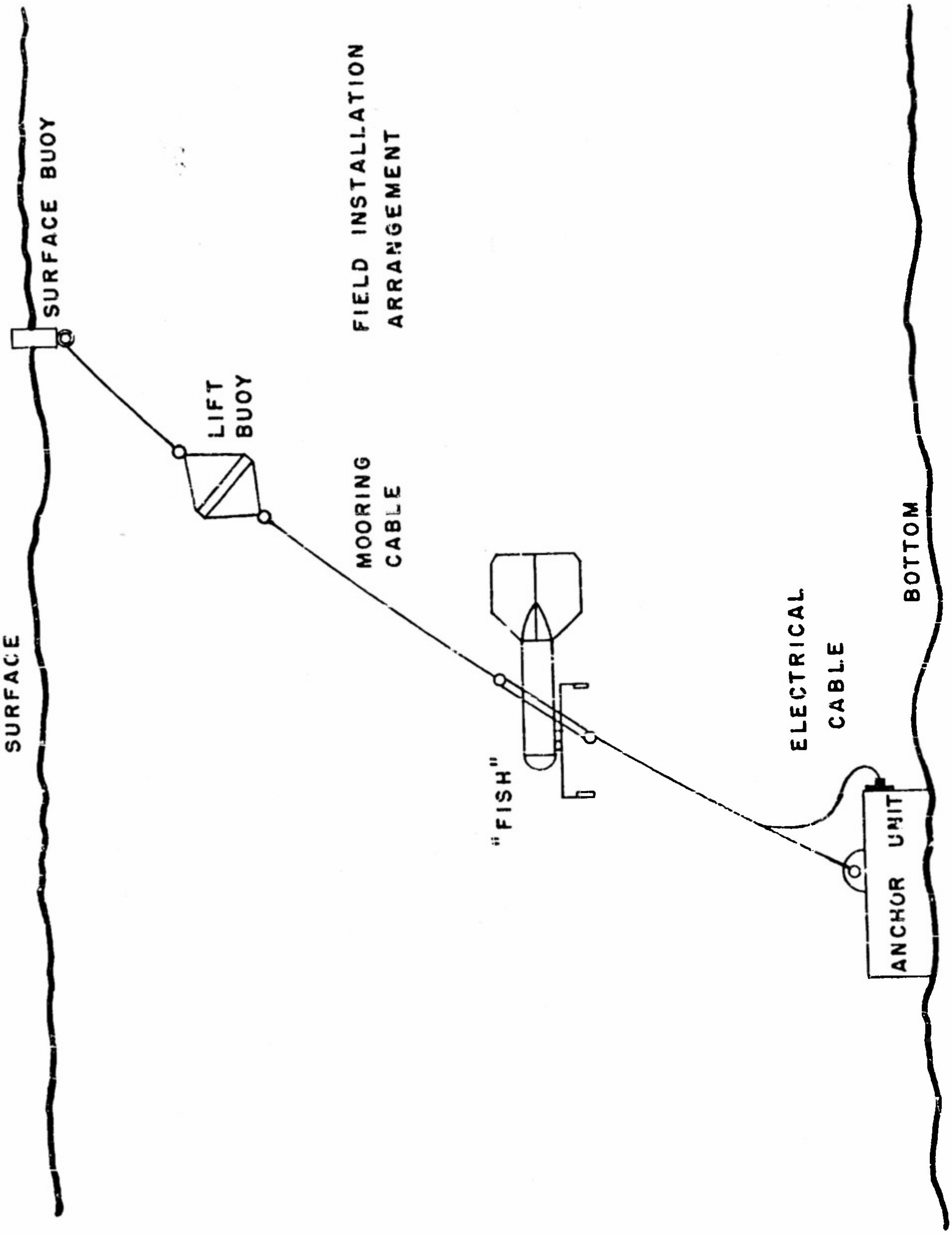
Fish Components:

Figure 4(a) is a photograph of the assembled fish, and shows the arrangement of the water-tight connector, the tail assembly, the nose and tail streamline fairings, and the ultrasonic head. Figure 4(b) is a photograph of the bottom of the interior of the fish, showing the coaxial switch, the phasemeter chassis, and the magnetic compass transmitter in their normal positions. The frame of this assembly is a 1/8-inch brass plate.

Coaxial Switch:

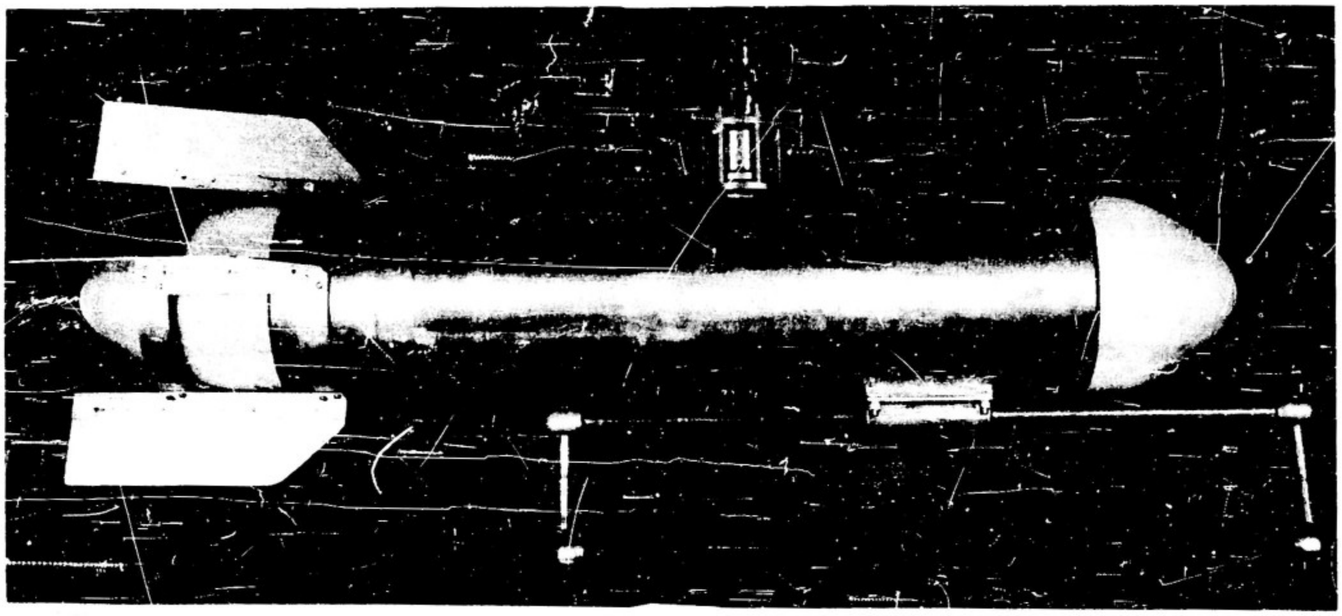
The coaxial switch is a Model 1460-30 double-pole transfer switch

FIG. 3

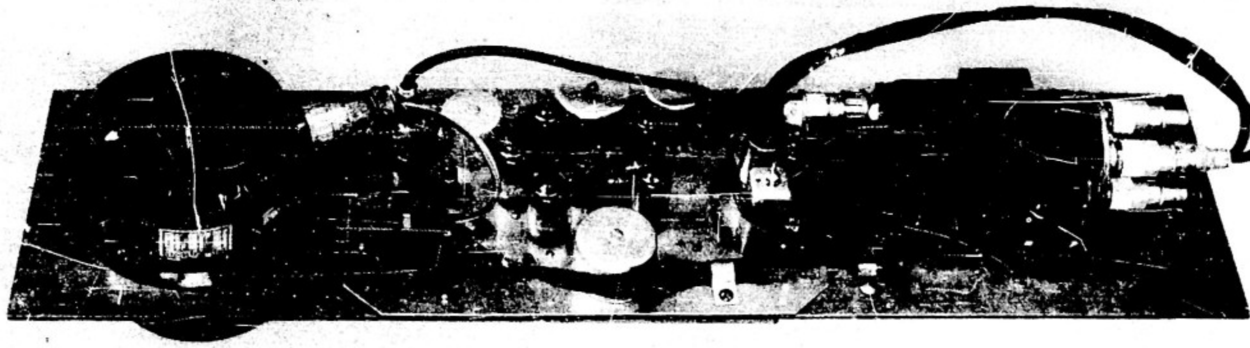


FIELD INSTALLATION
ARRANGEMENT
SURFACE
SURFACE BUOY
LIFT
BUOY
MOORING
CABLE
"FISH"
ELECTRICAL
CABLE
ANCHOR UNIT
BOTTOM

FIG. 4



(A)



(B)

and was obtained from Transco Products, Inc., Los Angeles, California. It is driven by a 24-volt d.c. motor, and requires approximately 0.7 second for operation. One of its characteristics of importance in this application is very low cross-talk since it serves the purpose of interchanging the two transducers. The transmitting transducer is operating at a much higher signal power level than is the receiving transducer, and any leakage between transducers will introduce errors in the phasemeter indication. The transducers connect to the coaxial switch by means of very short sections of RG-58/U cable and BNC coaxial connectors. The other RF connectors on the switch are connected to the chassis by means of similar cable and BNC connectors.

Magnetic Compass:

The compass is a General Electric Type KJ-1, Model 8KJ1AA Sub 1, rated at 26 volts at 400 cps excitation. The plastic case was slightly modified by machining to allow it to fit in the fish housing. It is provided with built-in magnetic compensation, and its output synchro is terminated on a four-pin Cannon connector.

Phasemeter Chassis:

Figures 5 and 6 together constitute the main circuit diagram of the phasemeter chassis. Figure 7 is a diagram of the cabling, and Figure 8 is a block diagram of the phasemeter. This last diagram will be discussed first since it will help in describing the principle of operation prior to going into the details of the schematic diagram.

The source of ultrasonic energy for the velocity meter is the driving oscillator which supplies acoustic power to the transmitting transducer. A portion of the output of this oscillator is fed to the reference channel mixer.

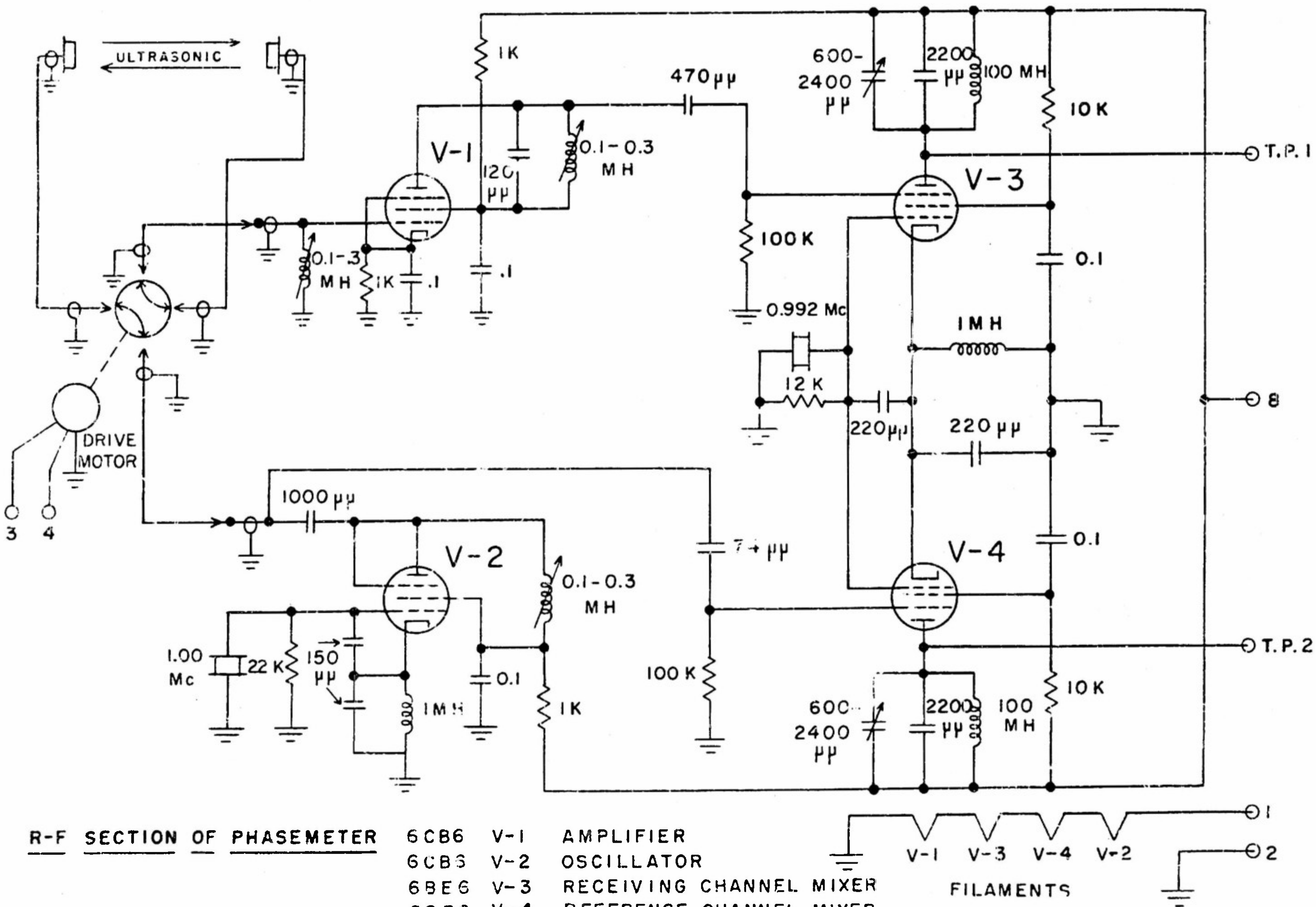
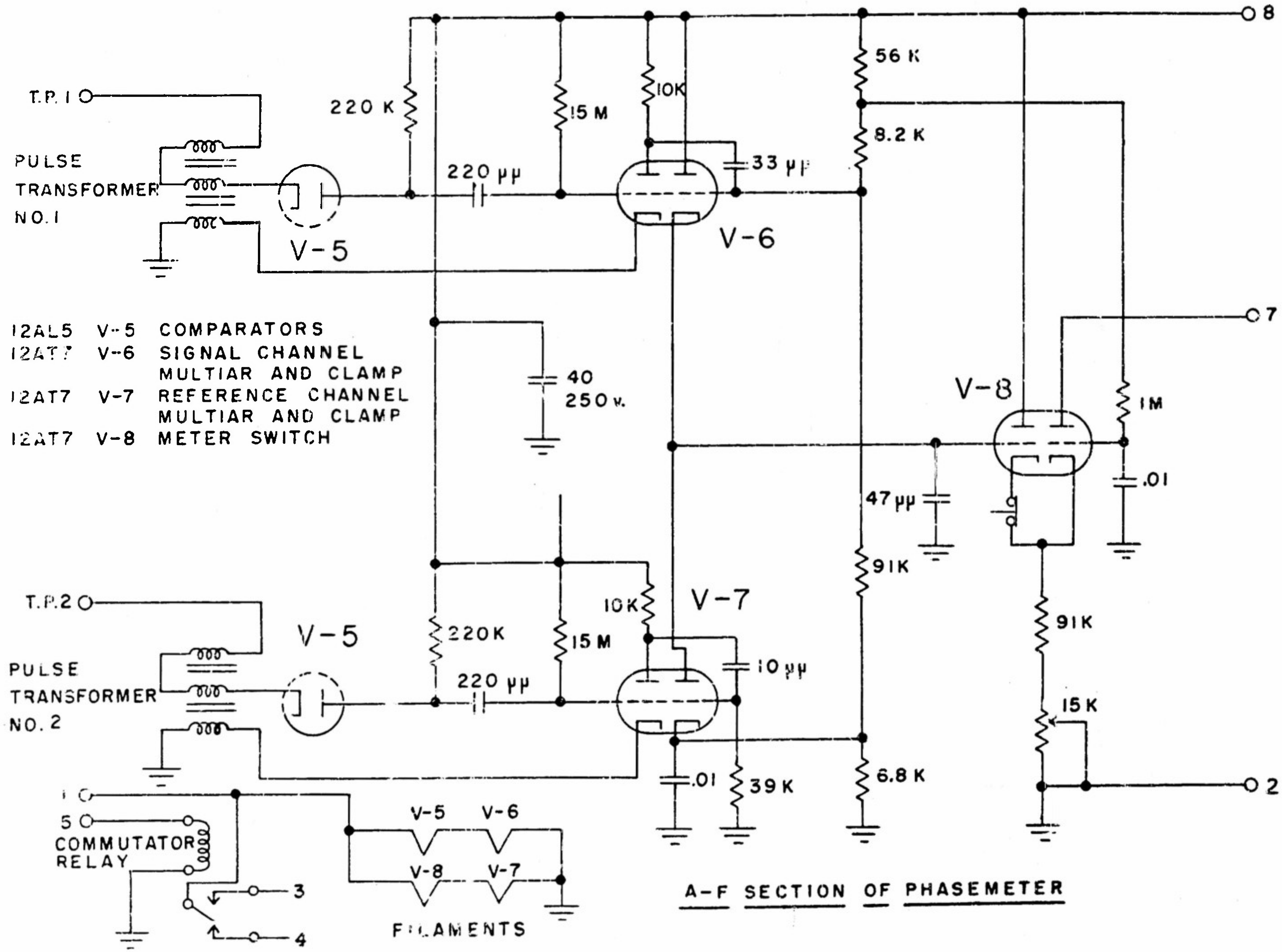


FIG. 5

R-F SECTION OF PHASEMETER

6CB6	V-1	AMPLIFIER
6CB6	V-2	OSCILLATOR
6BE6	V-3	RECEIVING CHANNEL MIXER
6BE6	V-4	REFERENCE CHANNEL MIXER

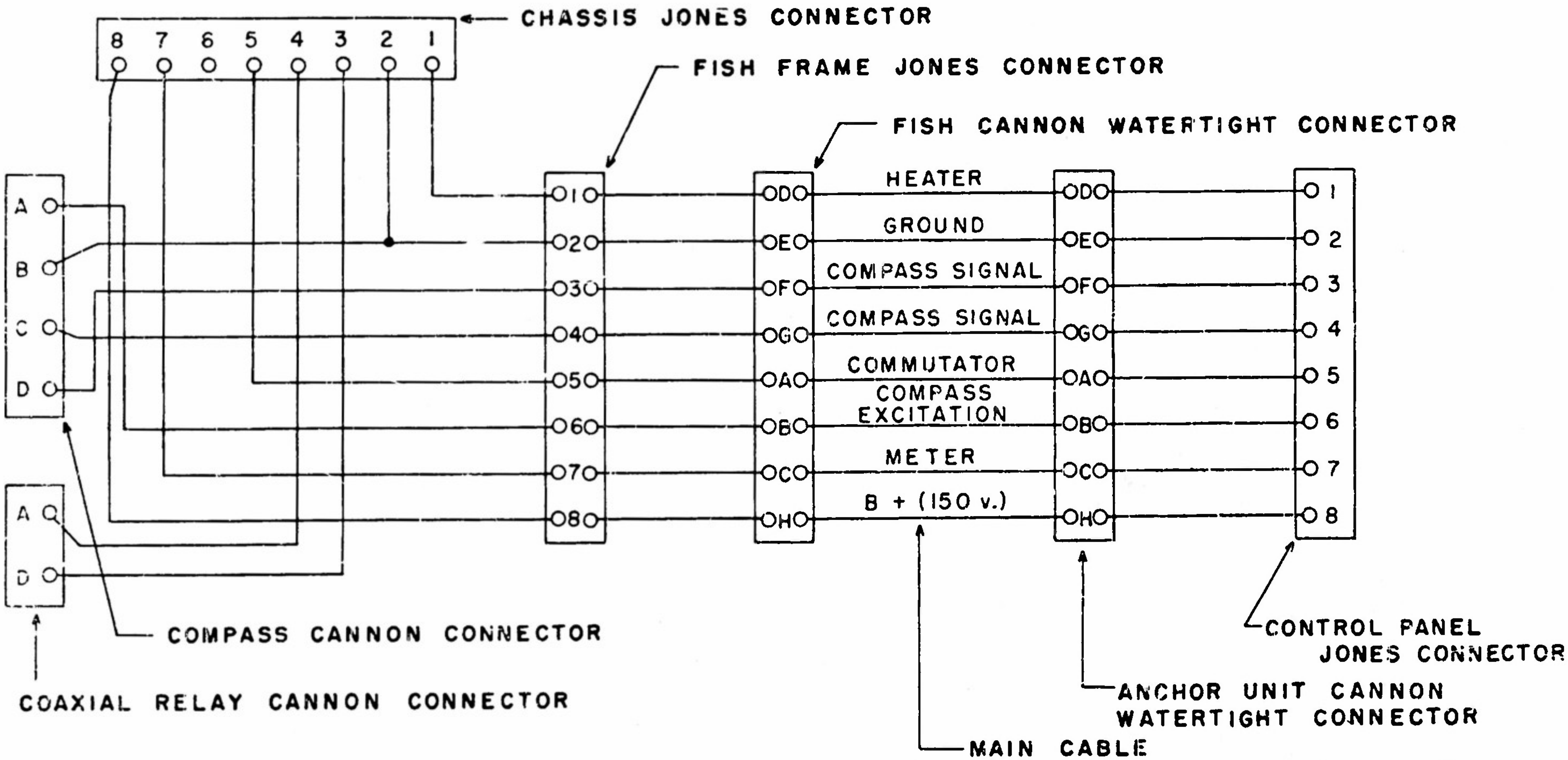
FIG. 6



12AL5 V-5 COMPARATORS
12AT7 V-6 SIGNAL CHANNEL MULTIAR AND CLAMP
12AT7 V-7 REFERENCE CHANNEL MULTIAR AND CLAMP
12AT7 V-8 METER SWITCH

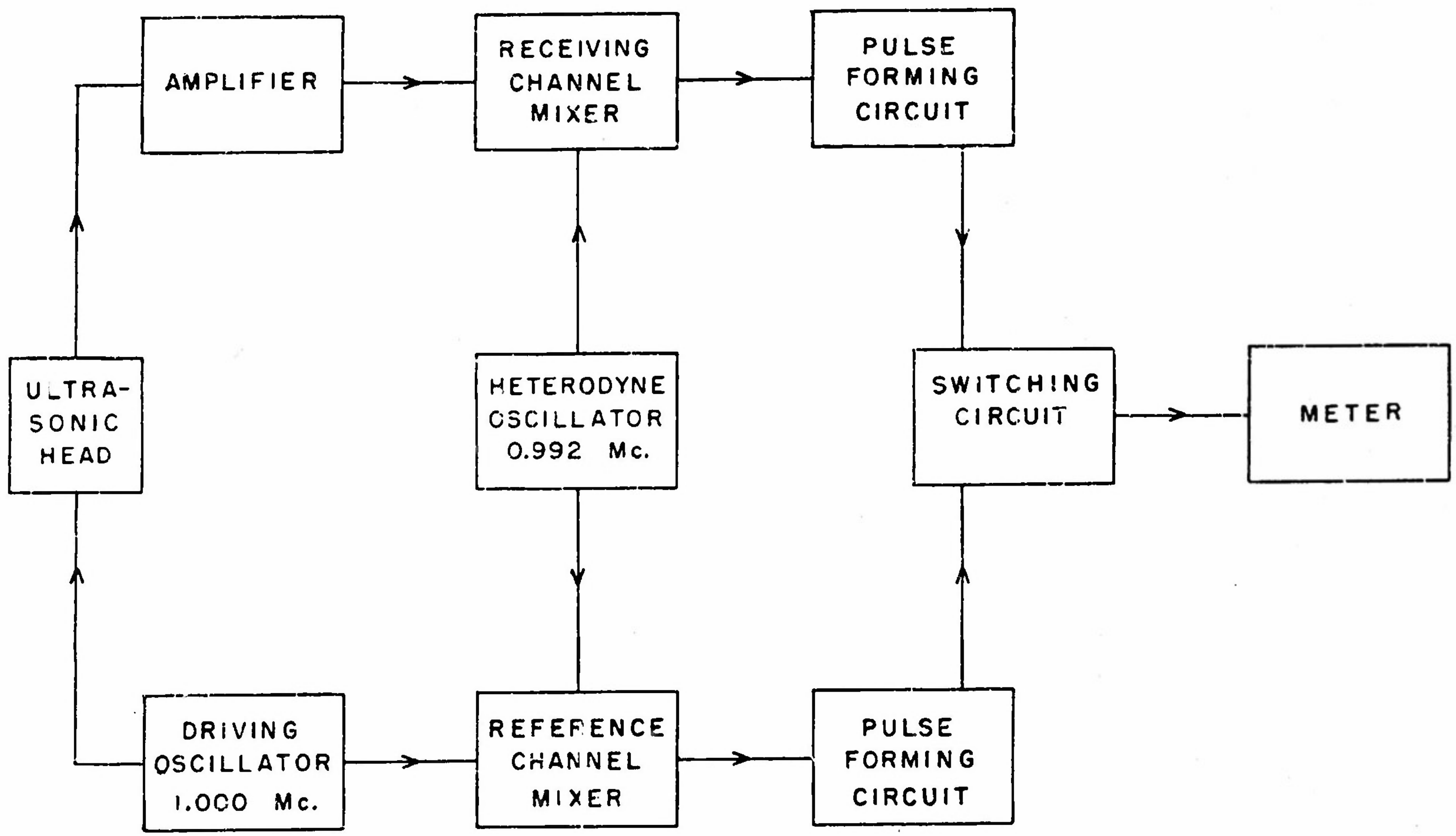
A-F SECTION OF PHASEMETER

FIG. 7



INSTRUMENT CABLING DIAGRAM

FIG. 8

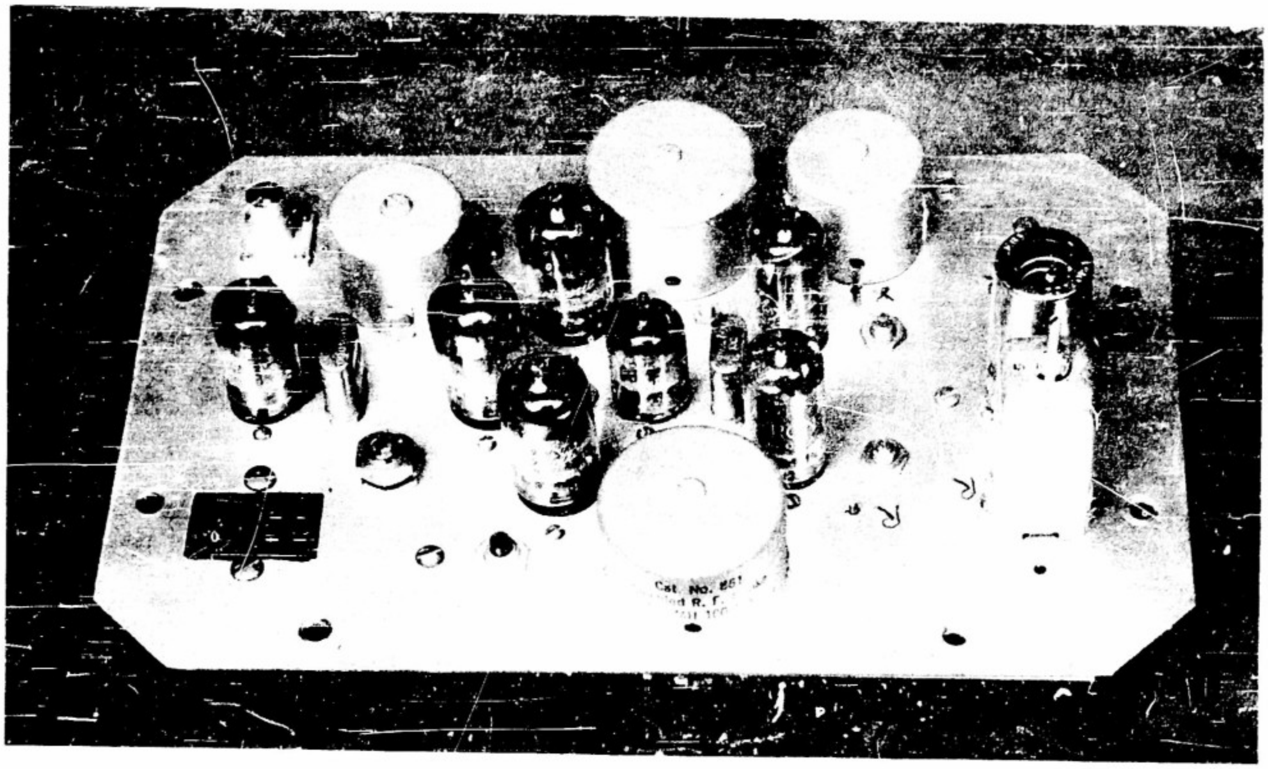


METER BLOCK DIAGRAM

The receiving transducer is connected to the amplifier which then feeds the signal channel mixer. All of the signals to this point in the discussion are at 1.0 Mcps. as controlled by a 1.0-megacycle crystal in the driving oscillator circuit. The heterodyne oscillator is crystal-controlled at 0.992 megacycles per second, and its output is available to each mixer. The output of the mixers consists of the two input frequencies (1.0 and 0.992 megacycles per second), their harmonics, their sum and difference, and sums and differences of the various harmonics. The mixer output circuits, however, are tuned to the difference frequency (8 kilocycles), and so all others are rejected. From this point on in the block diagram, all of the signals are then at 8 kilocycles, and this is the frequency at which the phase measurement is made. The phase difference between the two mixer outputs can be shown to be the same as the original phase difference between the ultrasonic signals.

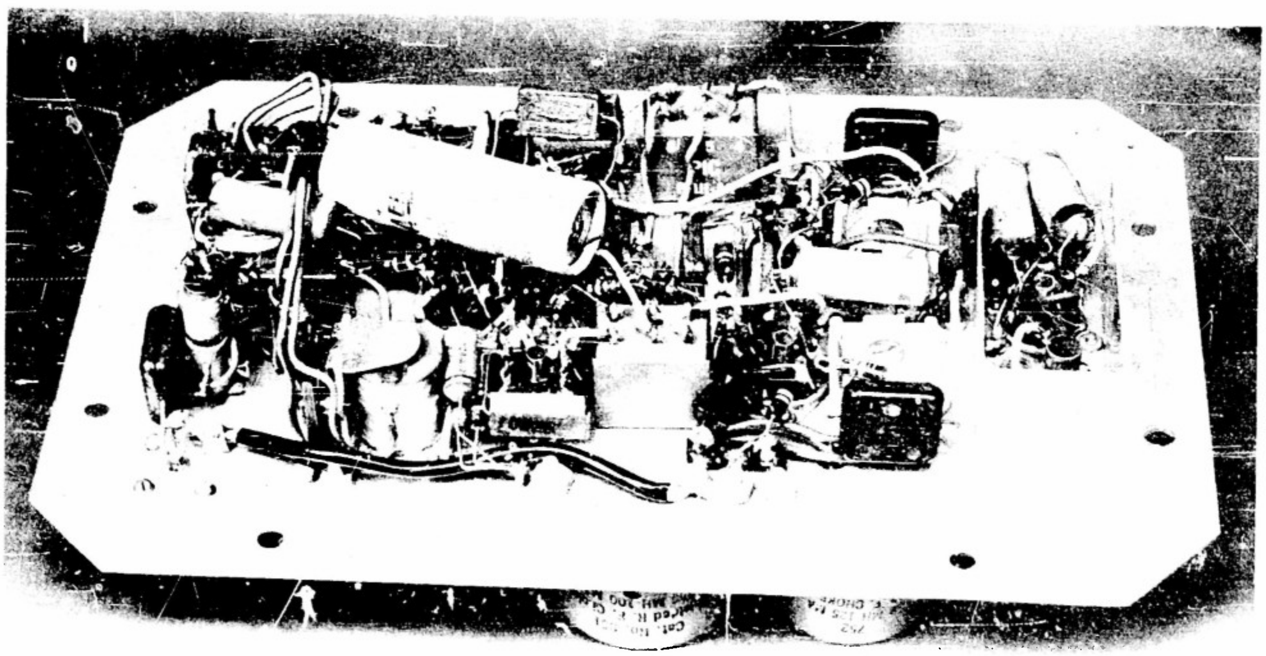
The 8-kilocycle output signals from the mixers are applied to the pulse-forming circuits where sharp pulses are generated which are related in time to the phase of the 8-kilocycle signals. These pulses are then applied to the meter switch circuit which provides a direct current of zero for zero phase difference, and which increases linearly to one milliampere as the phase difference increases to 360 degrees.

Figure 9 shows photographs of the top and the bottom of the phasemeter chassis, and one can see that all of the tubes are located on the top of the chassis along with all of the control and test points, such as coil slugs and trimmer condenser shafts. This arrangement makes it possible to connect an oscilloscope probe or a vacuum tube voltmeter to the test points, and accomplish the necessary tuning without removing the chassis from the fish frame. The



(A)

FIG. 9



(B)

two BNC coaxial connectors, the two oscillator crystals, the eight-pin Jones connector, and a pushbutton for calibration of the meter are also available from the top of the chassis. The remainder of the components of the phasemeter are located under the chassis, and are enclosed in a sheet metal cover for protection. In Figure 9(b) one can see a small sub-shield at one end of the chassis. This provides shielding for the receiving channel coaxial connector and the amplifier. This is the sensitive part of the circuit in that any leakage from the high signal level of the driving oscillator getting into the amplifier will cause a phase error. The rest of the circuit is relatively insensitive to leakage because of the relative signal levels and of the care used in layout and assembly.

The phasemeter is similar in some respects to several commercially available models, but Mr. K. S. Stull, Jr., who designed the circuit, incorporated some features of his own which made it possible to make it small, operate with a small amount of power, and use a minimum number of cable conductors. Reference to the schematic (Figures 5 and 6) will now be made to describe the circuits that have been built to accomplish the functions of the boxes in the block diagram.

Tube V-1 is the amplifier shown in the block diagram, and it is a single stage, tuned grid-tuned plate pentode amplifier, and its output is fed to tube V-3, the receiving channel mixer. The tuned grid circuit capacitance consists of tube input, stray wiring, coaxial cable, crossover relay, and transducer capacitance; therefore, all of these components are operating at high impedance. Tube V-2 is the 1.0 megacycle crystal-controlled, electron-coupled Pierce oscillator that provides power from its plate for the transmitting transducer. The tuning of this plate circuit is similar to that of the grid of V-1. As mentioned earlier, part of this oscillator's output is fed to the reference channel mixer, V-4 in the schematic. It is apparent from this diagram that the mixers, V-3 and V-4, also perform the function of the heterodyne oscillator shown in the block diagram. The cathode and first two grids of V-3 and V-4 are connected as an electron-coupled Pierce oscillator.

A lead is brought through the chassis from the plate of each mixer, and these are shown on the right-hand end of Figure 5 and the left-hand side of Figure 6 as T.P. (test point) 1 and 2. Measurement of the a.c. voltage at these two points will allow tuning of all of the tuned circuits while the phasemeter is in operation. Its amplitude is approximately 100 volts from peak to peak. The combination of the two pulse transformers, the two diode sections of V-5, and the two twin triodes, V-6 and V-7, are designed to produce very sharp positive pulses at the time the eight-kilocycle sine waves from the mixers cross their zero axis. On the positive half-cycle of the output of V-3 the top diode V-5 is not conducting. However, as the voltage swings through its a.c. zero axis (plate supply potential) going negative, the cathode of the diode is at an instantaneous potential equal to the plate potential, and the diode begins conduction. This conduction causes the voltage at the plate of the diode to follow the cathode negative. The left-hand grid of the triode V-6 is normally near ground potential, and V-6 is conducting, but its grid potential falls at this time because it is capacitively-coupled to the plate of V-5. This action results in the cut-off of the left-hand section of the tube V-6 and a rise in its plate potential.

This rise of potential is differentiated and applied to the right-hand grid of the same tube. The coupling from the left-hand cathode of V-6 through the pulse transformer accomplishes regeneration of the entire action just described so that the rise time of the pulse at the right-hand grid of V-6 is extremely short. The same action just described goes on in the reference channel circuit, except that the pulse at the right-hand grid of V-7 is related in time to the negative going axis crossing of the reference channel eight-kilocycle signal. Since the spacing between these two pulses is proportional to the phase angle between the two ultrasonic signals, it is only necessary to measure the spacing.

This measurement is accomplished by V-8, the meter switch tube, which is basically a one milliampere constant current meter supply which can be switched on and off. The tube allows this constant current to flow through the one milliampere meter for a length of time during each eight-kilocycle cycle equal to the time between signal and reference pulses. Therefore, the meter reads from zero to one milliampere, depending upon the phase angle as a fraction of 360 degrees. For example, a phase angle of 180 degrees will cause the right-hand section of V-8 to conduct at one milliampere for one-half cycle and at zero milliampere for the other half cycle, and since the inertia of the meter will not allow it to follow this eight-kilocycle switching rate, it will read the average value of 0.5 milliampere.

The switching action is accomplished by a two-volt change in potential at the left-hand grid of V-8. When this voltage is less than 98 volts, meter current flows, but when it is more than 100 volts, no meter current flows. This voltage can only be changed by changing the charge on the capacitor in the grid circuit. This is accomplished by the right-hand sections of V-6 and V-7. These tubes are normally cut-off so that any charge on the capacitor will remain relatively unchanged, and hold the left grid of V-8 at its last acquired potential. When a positive pulse is applied to the right grid of V-6, a pulse of cathode current flows and charges the capacitor to more than 100 volts. When a positive pulse is applied to the right grid of V-7, a pulse of plate current flows and charges the capacitor to less than 98 volts. From this discussion it can be seen that the pulses cause the meter to conduct from the time the reference channel signal crosses its axis going negative until the signal channel signal crosses its axis going negative.

The pushbutton that is available on the top of the phasemeter chassis is shown in the left-hand cathode of V-8. It is a normally closed switch which, when operated, cuts off the left-hand side of the tube allowing the right-hand side to conduct continuously through the meter. When this is done, adjustment of the calibrating potentiometer can be made while observing the deflection of the meter in the anchor unit. This will normally be set at one milliampere.

The tube filaments are connected in series-parallel to utilize the 24 volts of the battery directly, as shown on the diagrams.

The coaxial switch requires 24 volts on alternate leads to cause it to operate. In order to perform this function with only one lead in the main cable a small relay was installed on the chassis. Energizing this relay advances the coaxial switch. When the relay is deenergized, the coaxial switch advances again. When the relay coil is energized from the anchor unit, the commutator indicator light is lighted so that the data photograph taken at this time will show the direction of the ultrasonic transmission.

Ultrasonic Head:

Figure 10 shows the construction of the ultrasonic head by means of two sketches; one, the head itself, and the other, an exploded view of the transducer. It was necessary to make the transducer as streamlined as possible to minimize its effect on the water flow in the ultrasonic path. The crystals were purchased from the Bliley Electric Company of Erie, Pennsylvania. The specifications were as follows: X-cut quartz, 7/8-inch diameter, ground for thickness vibration resonance of one megacycle per second $\pm$ 0.1 per cent, with fired silver electrodes on both surfaces maintaining a free edge of 1/16 inch. A fine copper lead was requested to be soldered at the center of one face of each crystal. The diameter was determined by the desire for a narrow ultrasonic beam as discussed previously. At a frequency of one megacycle per second, the wavelength is 0.15 centimeter, and the active face diameter of the crystal is 3/4 inch which corresponds to approximately 12.5 wavelengths. The radiation pattern was measured roughly using experimental transducers in a tank of water in order that a check might be made on the design. This was considered important because of the necessary proximity of the acoustic path and the fish housing. In these tests it was found that the primary beam lobe had a semi-vertical angle of approximately six degrees. For this reason the acoustic path, for design purposes, was restricted to a minimum of 4 inches from the surface of the fish housing.

Since insulation of the leads to the crystals in the transducers is important, it was decided to use coaxial cable for this purpose because of its mechanical strength. The inner conductor of this cable serves the purpose of a binding post for the fine wire from the rear face of the quartz crystal. This lead is soldered to the inner conductor of the coaxial by means of the access plug on the rear of the transducer, after the coaxial is permanently in place.

The exploded view of the transducer shows the arrangement of the parts of the transducer. The crystal is seated on a bakelite backing ring. Prior to the use of this backing ring, a backing plate of the same material was used. It was machined to make it one-half wavelength in thickness, and then an attempt was made to determine whether the backing plate or the backing ring would accomplish a more efficient coupling of acoustic energy to the water. It was not apparent from these tests that there was any significant difference between the two.

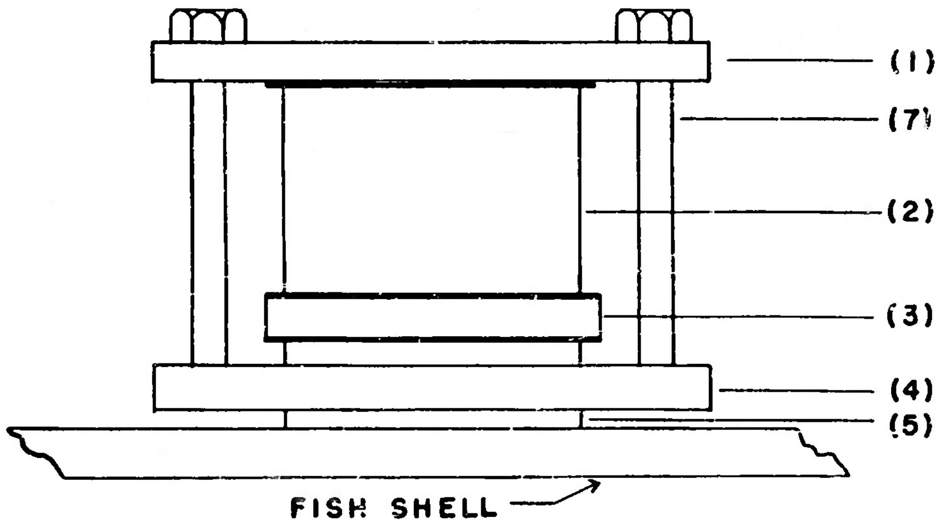
The cover ring and its mounting surface were so designed that when assembly is made and the screws are inserted, the cover ring comes into contact with the brass body of the transducer at a point such that the "O" ring squeeze is as it should be. The cover plate surface in contact with the "O" ring is sloped so that the "O" ring will seal the junction between the crystal and the backing ring, and the junction between the cover plate and the transducer body.

There was some concern before the transducer head was constructed as to whether or not acoustic energy would be transmitted from one transducer to the other via the brass tubes of the transducer head. It was thought at first that this might happen if the acoustic impedance discontinuity at the rear face of the quartz crystal was not sharp. Theoretically at least, if the acoustic impedance of a transmitting medium makes an infinitely abrupt change, no energy will be transmitted because all of it will be reflected. The characteristic acoustic impedance of a medium is equal to the density of the medium times the propagation velocity of the medium. From the book referenced earlier by L. L. Beranek, the impedance of air is approximately 43, as compared to approximately 150,000 for water and several times this last figure for quartz. From this it can be concluded that very little acoustic energy should be coupled to the air backing of the crystal, but most of it should be reflected from the rear face of the crystal and made available for transfer to the water at the front face of the crystal.

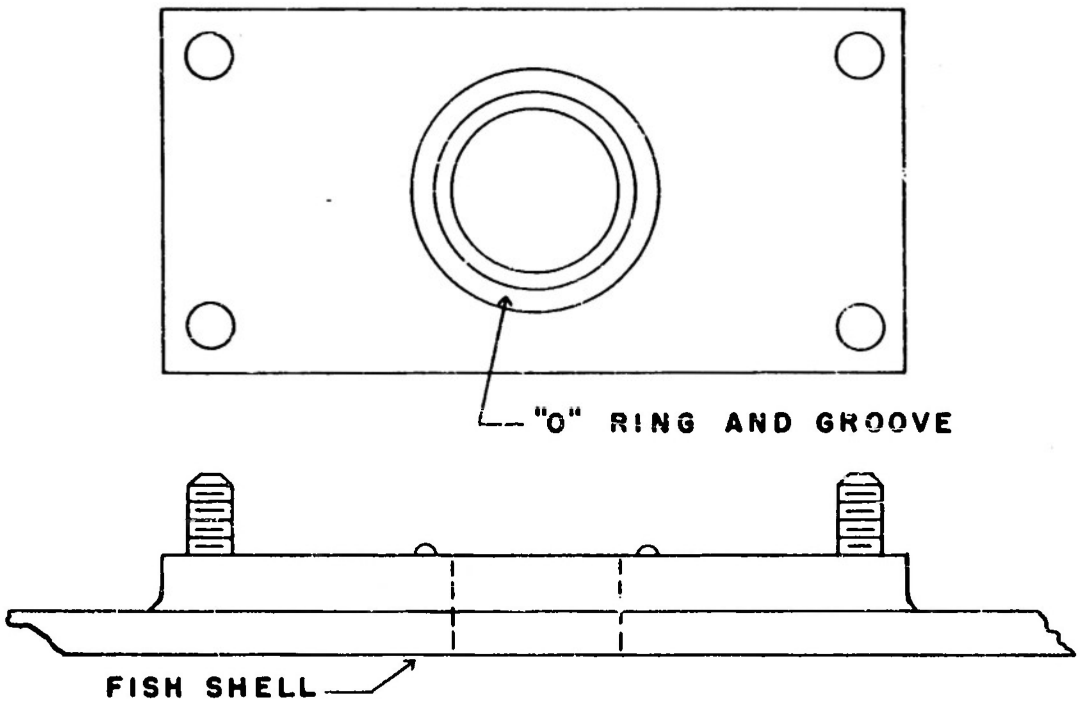
In order to see whether any acoustic energy was transmitted through the brass, a test was made by interrupting the acoustic path in the water and observing any signal that might be present on the receiving channel amplifier output. There was none that could be measured.

<u>Cable Connectors</u>

Figure 11(a) is a sketch drawn to illustrate the essential features of the water-tight cable connector and the transducer head attachment to the outside surface of the fish. The actual cable connector is a type W-22-18S-21, eight-pin connector obtained from the Cannon Electric Company of Los Angeles, California. The male part of this connector appears in the sketch as part (1). The connector is drawn down on the sleeve, (2); the pressure plate, (3); and the base tube, (5). All of the parts are separated by flat rubber gaskets (6). The six-threaded rods (7) serve to draw the parts together and to squeeze the gaskets. The base tube is soldered in place in a hole in the shell of the fish. The base ring (4) is pressed over the base tube and soldered in place.



(A) WATERTIGHT CONNECTOR (NOT TO SCALE)



(B) TRANSDUCER HEAD MOUNTING PLATE

The pressure plate is of 1/4-inch brass, and has eight feed-through terminals soldered on its surface. This plate is expected to resist the entrance of any water that might leak through the connector by way of a leak in the cable jacket outside of the connector. The water-tight connector on the anchor unit is of the same construction.

Figure 11(b) shows the "O" ring arrangement on the transducer mounting surface. There are four brass studs in this surface that draw the transducer head flange down against the "O" ring. A hole is drilled through the mounting surface, and the shell of the fish to permit the entrance of the two coaxial transducer leads and their BNC connectors.

Anchor Unit:

The anchor unit is a steel cylinder approximately four feet long by one and one-half feet in diameter. A photograph of the unit as it appears ready for operation is shown in Figure 12. It is closed at both ends by 3/8-inch steel cover plates, and the cylinder is divided approximately in half by a bulkhead of 1/4-inch steel. This bulkhead is to prevent any leakage of battery electrolyte from having a detrimental effect on the remainder of the anchor unit. The other end will subsequently be referred to as the recorder end.

Battery:

The battery cells used to energize the whole instrument are of the lead-acid type in clear plastic cases. They were obtained from the Willard Storage Battery Company of Cleveland, Ohio. The cells are Willard Type No. X25AH with a nominal voltage rating of two volts and a 25 ampere-hour capacity. The cases are provided with floating ball specific gravity indicators to pro-

FIG. 12

vide a quick visual indication of the state of charge of the cells. Twelve of the cells are mounted in two rows of six in a steel box. The box is welded to an angle iron frame, and the whole assembly can be removed by sliding this frame from the battery compartment of the anchor unit (Figure 13).

A fuse and a two-pin Cannon connector are mounted on the outboard end of the box frame to facilitate installation and servicing. The battery cable is permanently attached to the compartment bulkhead so that the battery box can be placed in its final operating position before the connector is attached to the box frame.

As will be explained later, the measured consumption of the instrument is approximately ten ampere-hours per week. This figure represents 40 per cent of the manufacturer's rating, providing a safety factor of 50 per cent based on the manufacturer's recommended energy drain limit. This would allow for an extra three to four days of instrument operation without the risk of battery damage if it became impossible to retrieve the instrument on schedule.

Recorder Unit:

As mentioned before, the remainder of the anchor unit consists of the recorder unit in the recorder end of the anchor unit shell. It can be seen in the photographs marked Figure 14 and Figure 15. A general description of the recorder unit will be given prior to going into the details of its components.

Mechanically, the unit consists of two 1/8-inch aluminum plates, nine by ten inches in area, which are coupled together by aluminum channels at the top and aluminum bars at the bottom. These bars at the bottom serve

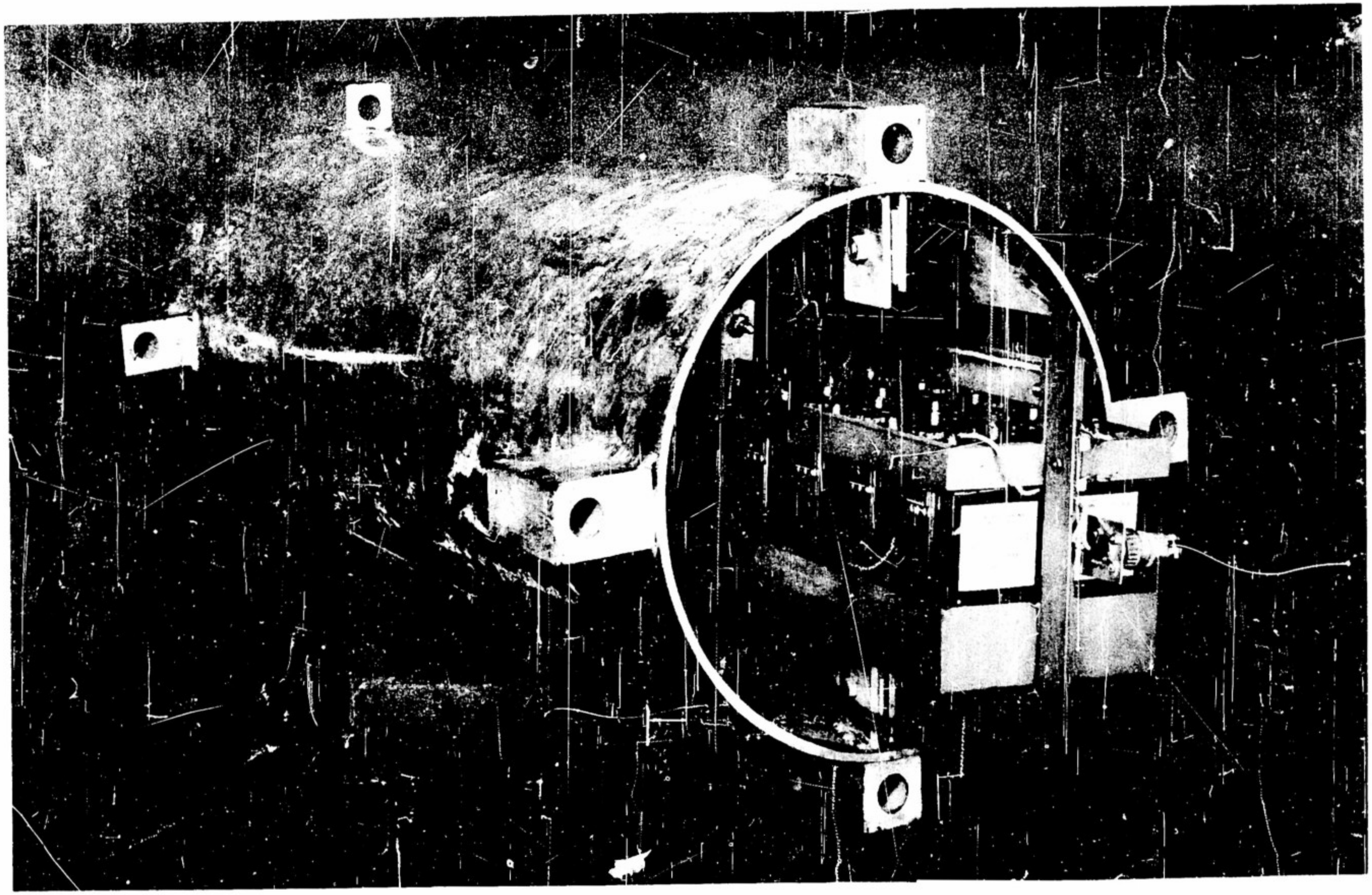


FIG. 13

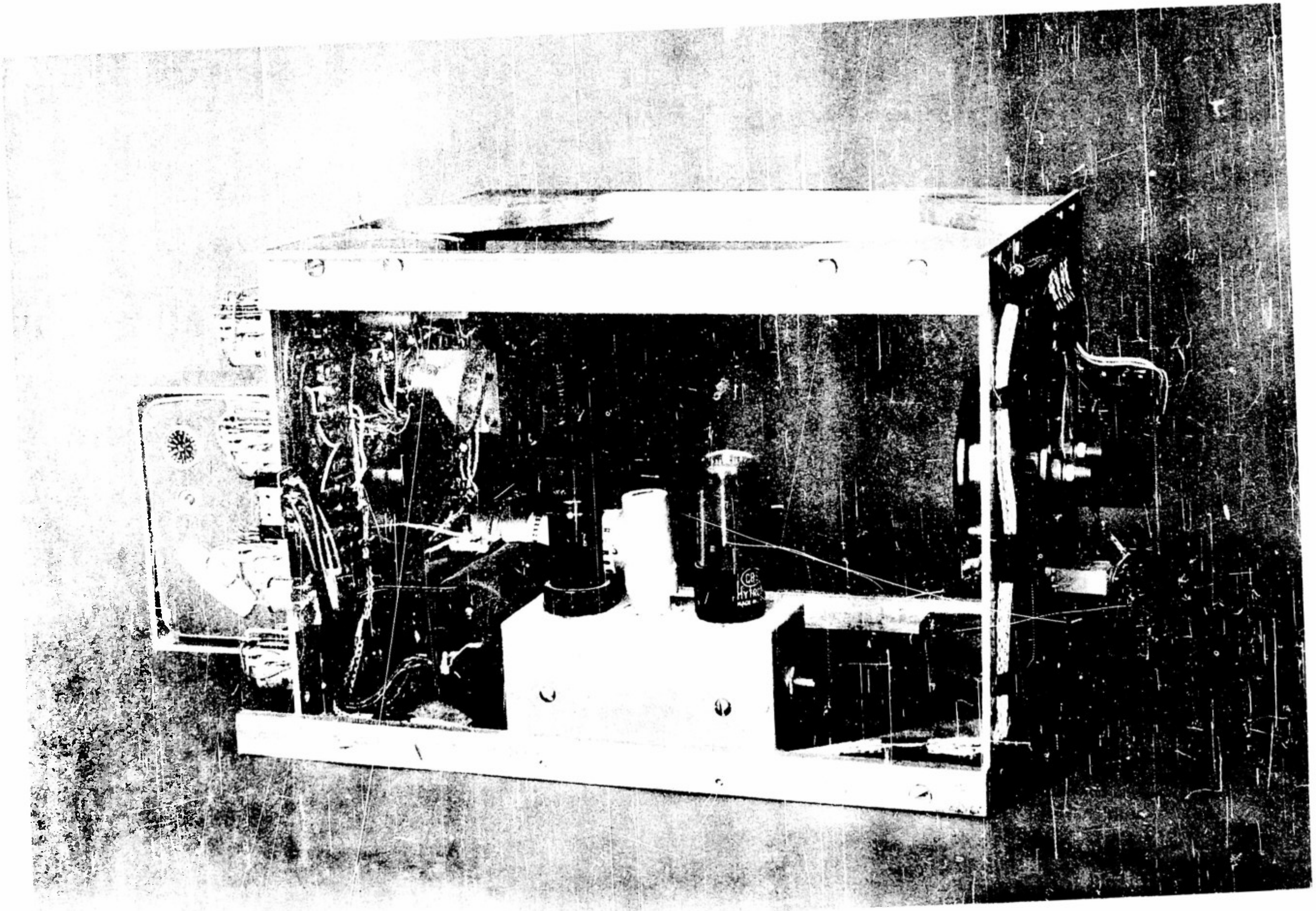


FIG. 14

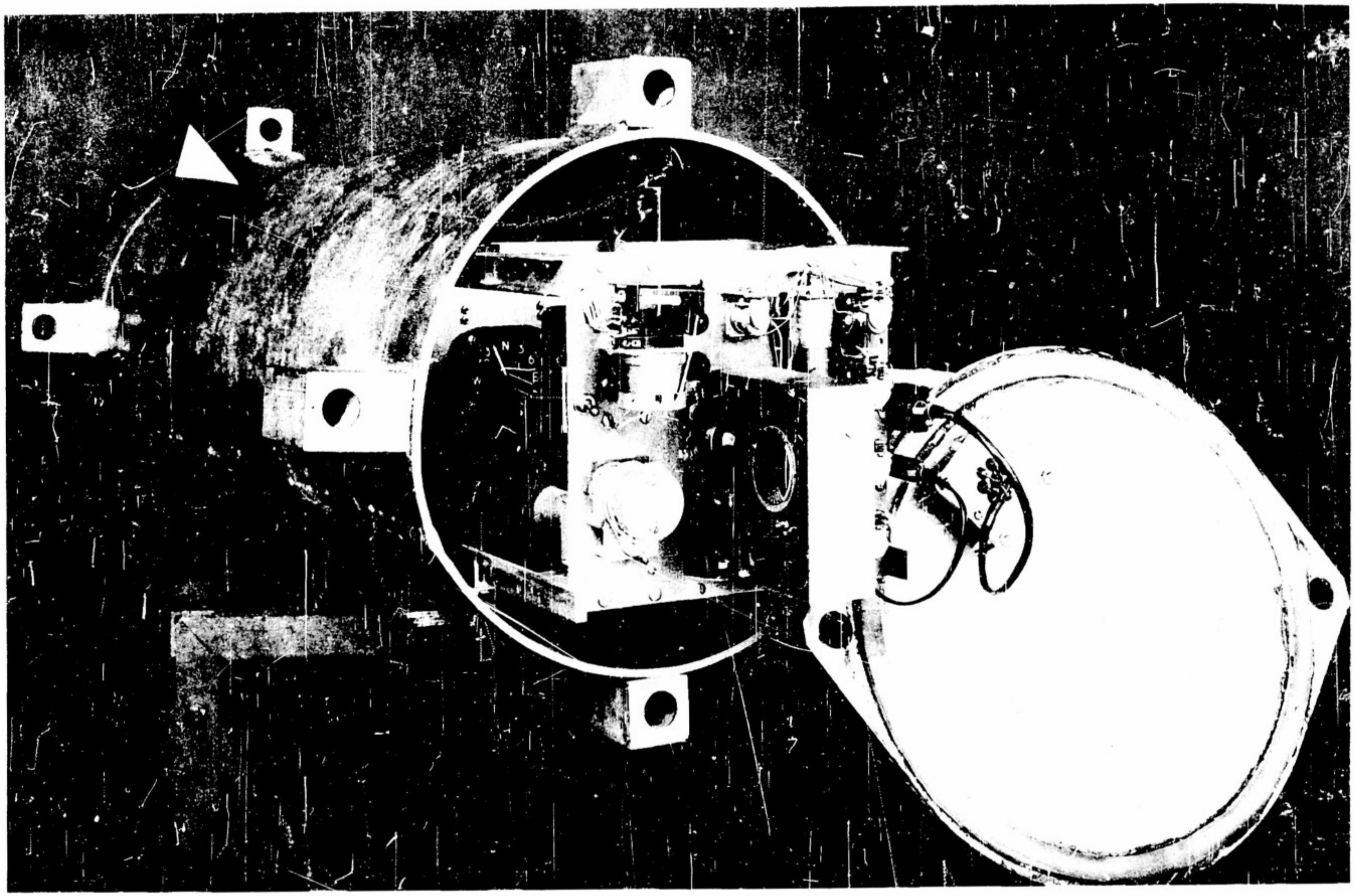


FIG. 15

as runners supporting the recorder unit on the tracks which are permanently mounted in the recorder end of the anchor unit shell.

The left-hand plate, as it appears in the photograph, supports all of the control components and circuitry for the instrument. It also carries the camera, the camera light, the primary and secondary timers, the dynamotor, the 400-cycle inverter, the control pushbuttons, the indicator lights, the cable connector, the battery cable connector, and two six-point barrier terminal strips. This plate will subsequently be referred to as the control panel.

The small three-tube chassis appearing in the center of the photograph is the power supply regulator. The right-hand plate will be referred to as the camera display. It holds the milliammeter, the compass repeater, the commutator indicator light, a terminal strip, and an eight-day spring-driven clock.

Control Panel:

The control panel can be seen in the photograph of Figure 16, in addition to Figures 14 and 15. When the cover of the anchor unit is removed and the recorder unit is in place in the shell in its normal position, this front surface of the control panel is the outermost part of the recorder unit. This arrangement was used in an effort to facilitate the operation and servicing of the instrument. For purposes of observation, the recorder unit can be operated with the unit pulled out of the anchor unit shell approximately half-way. The camera display panel is readily visible to an operator when the unit is so pulled out. In fact, the normal procedure for launching the instrument would include this kind of an operation just prior

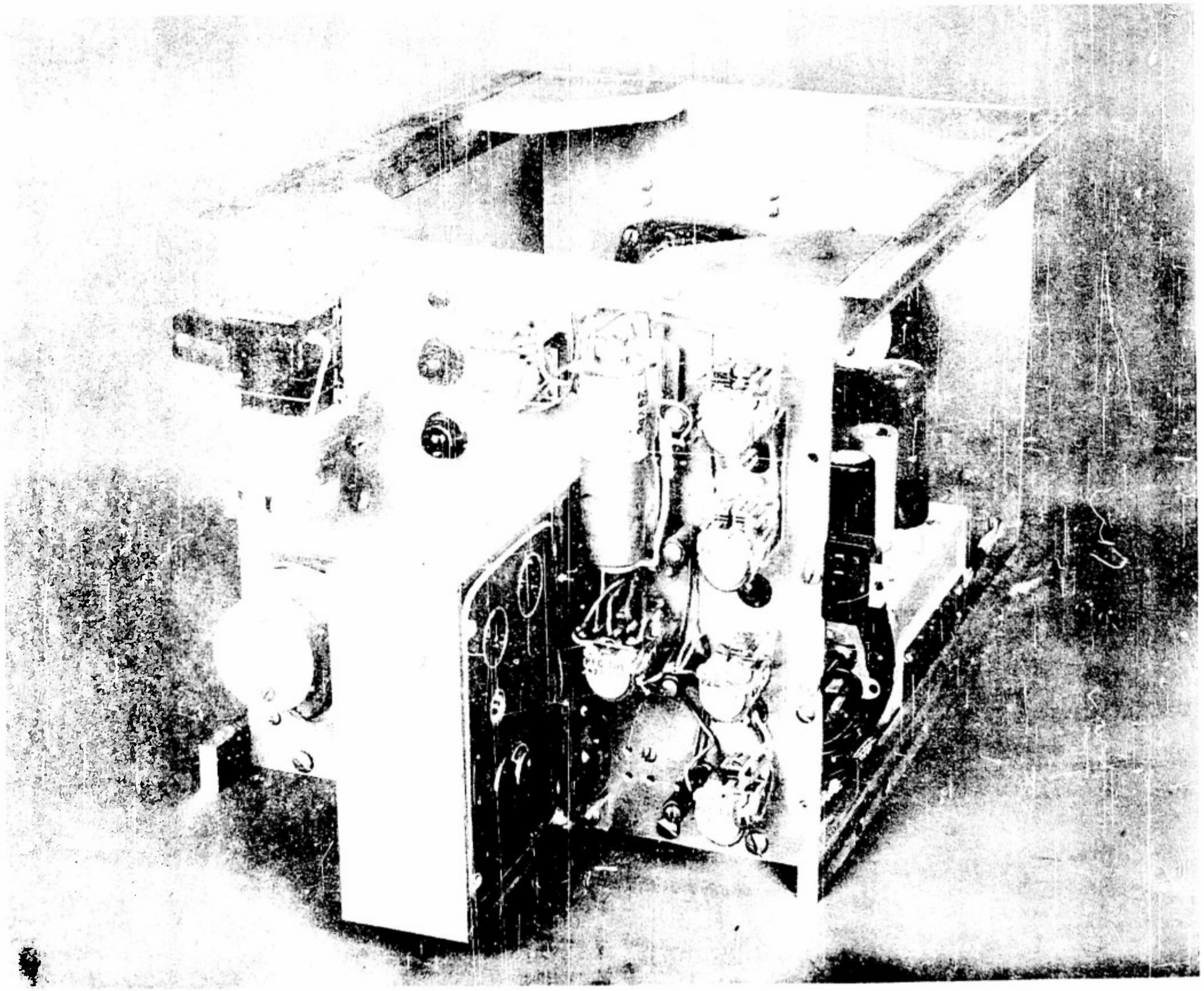


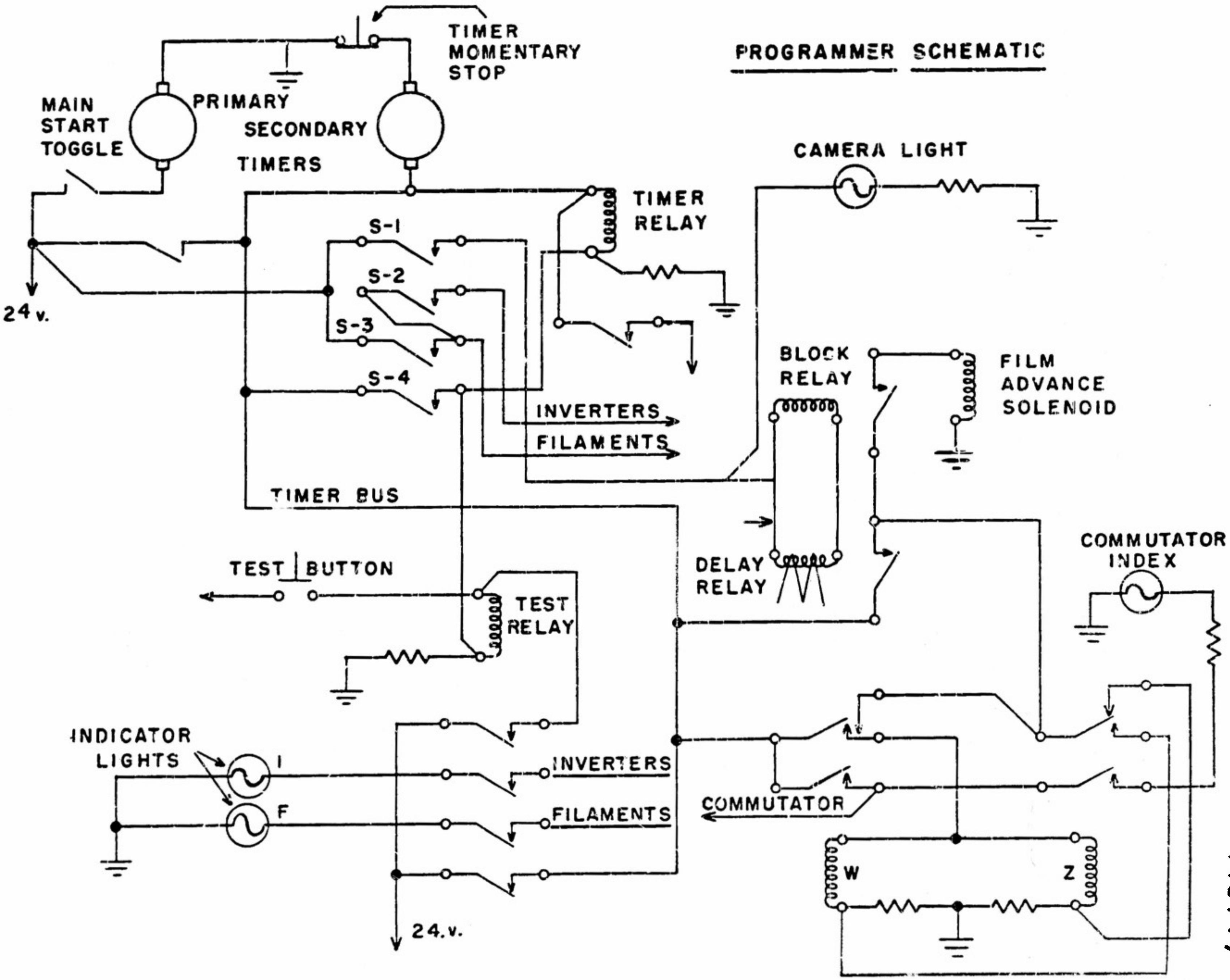
FIG. 16

to putting the shell cover in place. It will later be clear just how this can be done.

Instrument Program:

It was decided at the outset of the development of the ultrasonic current meter that the design should be as versatile as possible. This feature was particularly important in regards to the instrument programmer since flexibility here would permit many different modes of operation of the meter. As the discussion goes along, these points of flexibility will be discussed.

Figure 17 is a circuit schematic of the instrument programmer as it is now connected. The dotted lines represent connections that can be made readily to effect a desired change in the operating cycle. The primary and secondary timers are similar 24-volt d.c. timers obtained from the A. W. Haydon Company in Waterbury, Connecticut. The motors are designated as Haydon Series 3600, and the primary timer motor has a camshaft speed of two revolutions per hour. The secondary timer camshaft rotates at one revolution per minute driving five cams, which were fabricated by Haydon to our specifications. Two of these cams perform the function of S-1 on the secondary timer, and this is because the manufacturer suggested that one cam could not be readily built to close a switch for one second on three-second intervals. Presently, for reasons that will be apparent later, the switch S-1 is connected to provide one-second pulses at the times 30 and 36 only. However, a simple jumper connection between the top two switches of the secondary timer will provide pulses at times 30, 33, 36 and 39 in the sixty-second reading cycle.



PROGRAMMER SCHEMATIC
TIMER MOMENTARY STOP
MAIN START TOGGLE
PRIMARY
SECONDARY
TIMERS
CAMERA LIGHT
TIMER RELAY
S-1
S-2
S-3
S-4
24 v.
BLOCK RELAY
FILM ADVANCE SOLENOID
INVERTERS
FILAMENTS
TIMER BUS
DELAY RELAY
COMMUTATOR INDEX
TEST BUTTON
TEST RELAY
INDICATOR LIGHTS
I
F
INVERTERS
FILAMENTS
COMMUTATOR
W
Z
24.v.

FIG. 17

The primary timer is started by means of the start toggle switch which is located on the control panel at the extreme left-hand edge. This switch would normally be thrown to the on-position at the last minute before putting the anchor unit cover in place. This primary timer is the only component in the instrument that runs continuously, and its current drain is approximately 50 milliamperes. Its only function is to start the reading cycle (secondary timer) on approximate one-half hour intervals. These intervals are expected to deviate from thirty minutes as much as 10 per cent, but this is not important since the clock is photographed with each meter reading, and the time of the reading will be so established.

The secondary timer may be started by either the primary timer or by the "test" button which is mounted at the top just to the left of the center of the control panel. This pushbutton is provided so that a reading cycle may be run through just prior to launching the instrument while an operator is present and can observe the operation.

There are seven relays, and one solenoid on the control panel, all of which were obtained from the Price Electric Corporation of Frederick, Maryland. These will be named for reference purposes with the Price type numbers. At the right-hand edge of the control panel is a column of four relays. From top to bottom these are: W relay, type 5797; Z relay, type 5711; the photo relay, type 5703; the timer relay, type 5701. The large relay at the top again is a copper slug, slow-operate relay, type 5910, which is called the pulse-delay relay. Just below this is the test relay, type 5722. Just above the camera box is another relay which serves to deenergize the film advance solenoid between stepping pulses. This solenoid is located between the camera and the control panel below the camera lens, and is mounted on the camera box. It operates the button on the camera that advances the film, one frame at a time.

Just below the "test" button are two jeweled indicator lights, and below them another pushbutton. This button is provided to permit testing the camera light without the necessity of running through a complete reading cycle. A third pushbutton is mounted on the secondary timer frame, and it can be used to stop the secondary timer at any point in the reading cycle to allow checking the circuit operation, tuning the phasemeter, or calibrating the full scale position of the milliammeter in the camera display.

The two indicator lights on the control panel do not light during a reading cycle unless the reading cycle was started by means of the "test" button. The top light gives an indication of the application of plate supply voltage to the circuit, and the bottom light indicates that filament power is being supplied to the circuit. When the reading cycle is automatically started in the normal way by the primary timer, these lights will not operate because the test relay will be unenergized. This is necessary because the camera has no shutter, and the exposure of the film is controlled by the camera light.

The timer bus is available at many points on the control panel. This is so because the timer bus is deenergized at the end of a reading cycle, and this feature of the timer bus would be useful in assuring the deenergized condition of all circuits and relays at the beginning of the next reading cycle. Except for the high current circuits, such as the inverters and the primary timer, all of the instruments are energized from this timer bus. In normal operation, the timer bus is held in the energized state through the reading cycle by the timer relay. It is deenergized by S-4 of the secondary timer at time 59, applying a one-second, shunt-down pulse to the ground side of the timer relay. At this time the timer relay has 24 volts applied to both sides of its coil, and it therefore drops out. Incidentally, this is the reason why the test button must be held down for approximately one second before the secondary timer will keep running. The timer motor must advance to the point where S-4 opens to release the shunt-down on the relay, permitting it to pull up and lock up.

The reading cycle is arranged in such a way that the filaments in the voltage regulator chassis and in the phasemeter chassis in the fish are energized immediately at the beginning of a reading cycle. This is accomplished by S-3 of the secondary timer, which stays closed from time zero to 40 seconds. As mentioned earlier, this particular circuit and the inverter circuit (S-2) receive power directly from the 24-volt bus from the battery unit.

Switch S-2 is closed by its cam on the secondary timer at time 28 seconds, and stays closed until time 40. Since the filaments are warmed by this time, there is only the possibility of transients after the inverter has come up to speed. Tests to date on the instrument indicate that the time delays involved are adequate to permit stabilization of the circuits and meters, and if such is ever not the case, changes in the program can very readily be made. In fact, the time in the reading cycle from 40 to 59 seconds serves no purpose, except to be available with no major change in the components of the instrument. The circuits indicate in tests that they can stabilize with 18 seconds of filament warm-up time. Actually, 30 seconds are provided. If more time were needed, any one or all of the cams could be rotated on their shafts to allow a full minute for the reading cycle. It should be mentioned, however, that any extension of such periods as the filament warm-up period would increase the battery drain, and this should not be done without consideration for battery life and charging problems.

There are two different methods of turning on the camera light in the control circuit. The first one tried employs the photo relay to discharge a 1,000-microfarad condenser through the light bulb. The exposure can be controlled by changing the capacitance, or by using a different light bulb. To obtain a relatively short exposure with sufficient intensity requires that the light bulb be operated at voltages above its rating. This could be done, but not without some sacrifice of light bulb life. For this reason, a second method of controlling the film exposure was devised.

As described earlier, the secondary timer contact S-1 is actually two contacts driven by two cams. The second cam is displaced from the first so that they provide alternate pulses. The timing diagram, Figure 18, shows that there are four one-second pulses from S-1. The first and third are used in the control circuit for such functions as film advance. The second and the fourth are used to turn on the camera light. The exposure can be controlled simply by inserting a resistor in series with the bulb of the proper size to limit the light bulb current to an amount that produces a satisfactory exposure. The exposure time is fixed at approximately one second.

This last described system employing the second and fourth pulses from the secondary timer contact S-1 is the one presently used. However, there could very well be reason to prefer the first system for some purposes, and this can be accomplished quite easily. It would involve the changing of two or three jumpers in the control circuit and replacing the light bulb with one with a substantially lower voltage rating. The condenser is still in place, and could be used should the need arise. An example of an operation that might be better accomplished by this condenser discharge system would be a check of the reproducibility of the meter in field use. It would provide more readings in a shorter period of time since each reading cycle would obtain two upstream and two downstream readings. Other such cases might originate with the oceanographers who use the meter.

The W-Z relay combination is a standard one, sometimes called a relay "flip-flop". It is so called because of the fact that alternate pulses in a series of identical pulses have different effects on the circuit. The way this feature is applied here is the first pulse from the delay relay performs the entire process of exposure of the film, and at the same time it readies the instrument for the next pulse which will have exactly the same effect with one exception; the commutator relay on the phasemeter chassis in the fish will be energized. This, of course, results in a reversal of the direction of transmission of the ultrasonic path. The operation of this relay is also indicated on the camera display panel by the lighting of the commutator indicator light. It is then possible to ascertain on each exposure of film whether the direction of acoustic transmission was upstream or downstream when the reading was obtained.

Figure 18 shows the complete timing sequence of the reading cycle. The first delay pulse advances the film and energizes the W-relay. The end of this first pulse energizes the Z-relay, and when both of these relays are energized, the commutator relay on the phasemeter chassis is energized, and so the coaxial switch advances. Both the W and the Z relays stay energized until the beginning of the next delay pulse, at which time the W relay drops out. This, of course, deenergizes the commutator relay and produces another commutator advance. At the end of this second delay pulse the Z relay drops out.

Camera:

The camera is an 8-millimeter camera made by Bell & Howell, and designated as Model 172. The reason for the choice of this camera is primarily that it incorporates the control mechanism necessary to advance the film one frame at a time. The supplier of the camera was asked to remove the shutter mechanism from the camera so that the lens would remain open all the time. This would eliminate all problems of synchronizing the shutter and the other operations in the reading cycle, and exposure could occur anytime the light was turned on. The exposure can be controlled by means of the aperture stop on the lens and by the intensity of the light bulb.

The camera is rigidly mounted in a 1/8-inch brass frame which is in turn attached to the control panel. A 6.5-millimeter wide-angle lens was used, and since it is longer than the standard lens for this camera, it was necessary to drill a large hole in the control panel to permit the lens to extend through.

The lens axis is approximately lined up with the center of the camera display, and the camera light and its chrome-plated reflector are offset somewhat from this line to minimize direct reflection from the glass meter faces.

As viewed facing the control panel, the camera winding key is folded over against the right-hand side of the camera. On the lower left-hand side of the camera at the bottom is a small button which locks the magazine housing door. With this button in the "up" position the door is locked. In the "down" position the door will open, and the film magazine may be removed by pushing the magazine ejector button. This is located on the right-hand side of the camera just above the winding key.

The magazines for use in this camera are loaded with 16-millimeter film which is exposed one-half at a time. After the film has been run through the camera once, it may be run through again, exposing the other half of the film by removing the magazine from the camera and turning it over. Instructions concerning this operation are printed on the magazines, and the magazines are marked for a "first exposure" and a "second exposure". In practice, it is not likely that the film will be exposed on both edges because when an operator is available to turn the magazine around and to wind the camera spring, the magazine will contain one week's data. The cost of the magazine is not large enough to warrant waiting an extra week for the data, except in the case where the data are taken with an operator present.

The speed dial on the right-hand side of the camera at the top should always be set at the 16-frames per second position. This is suggested by the camera manufacturer. The other dial on the right-hand side of the camera at the top is a footage indicator, and it is driven by the film magazine.

The film advance solenoid is located below the lens on the front of the camera, and is screwed to the camera supporting frame. Service work on this solenoid can be best accomplished by removing the entire camera assembly from the control panel by means of the four brass machine screws that extend through the control panel.

One winding of the camera spring will permit the exposure of approximately 800 frames of data. At the rate of two exposures per reading cycle, one week's data will consist of 672 exposures. This results in 128 spare frames, or a little over one day's data. For this reason, the camera spring should be wound completely just prior to launching the instrument. It should be made clear that this limitation is on the camera spring, and not on the camera magazine. The magazine contains the order of five times the number of frames that can be exposed after one winding of the spring.

400 cps Inverter:

The inverter is a surplus item, and was obtained at the same time as was the compass. It is apparently the inverter manufactured for this purpose. It was made by the Pioneer Instrument Division of the Bendix Aviation Corporation of Newark, New Jersey. The machine is rated at 24 volts d.c., one ampere on the motor end, and 400 cps, 6 volt-amperes, 26 volts on the generator end. The two-pin connector that was installed on the inverter has been removed to accomplish a saving in space. The base on which the inverter is mounted contains the components of a filter, probably required for the elimination of interference with aircraft radios. This machine is mounted at the bottom of the rear of the control panel.

Dynamotor:

The dynamotor is also a surplus item manufactured by Westinghouse Electric & Manufacturing Company, and bears the Style No. 1171187A. The motor end rating is 27 volts d.c. at 1.4 amperes. The generator end is rated at 285 volts d.c. and 0.060 ampere. The output voltage of this dynamotor of course varies a great deal with changes in the battery voltage and with changes in the load current.

Power Supply Regulators

Because of the large variations in the output voltage of the dynamotor and the sensitivity of the phasemeter to such changes in plate supply voltage, it was necessary to design and build a power supply regulator. This design was made by K. S. Stull, Jr., and its circuit schematic diagram is shown in Figure 19. This is a series tube type voltage regulator employing a 25L6 as the regulator tube. A 5651 is used as a voltage reference tube, and a 12SH7 is the control amplifier tube. The expected range of variation on the terminal voltage of the batteries is 22 to 24 volts. Figure 20 is a plot of the data obtained in a test to determine the performance of this regulator. The input voltage to the regulator was varied from 14 to 28 volts, while the load current was maintained constant (as it will normally be) at 35 milliamperes. The output voltage was as nearly constant as could be read on a good voltmeter over the range of 22 to 28 volts. The satisfactory regulating range is seen from this plot to be extended as low as 20 volts, a condition well below the expected minimum level of battery reserve.

The regulator was built in a totally enclosed chassis with only the tubes, the control potentiometer shaft, and the six-pin Jones connector on the outside. After removing the connector, the complete regulator can be removed from the instrument by removing the chassis cover screws. The adjusting potentiometer appears in the circuit diagram in the control amplifier's control grid circuit to ground. The filaments of the regulator are energized by the same means as are the phasemeter filaments, and the same warm-up period is available here before the dynamotor is started.

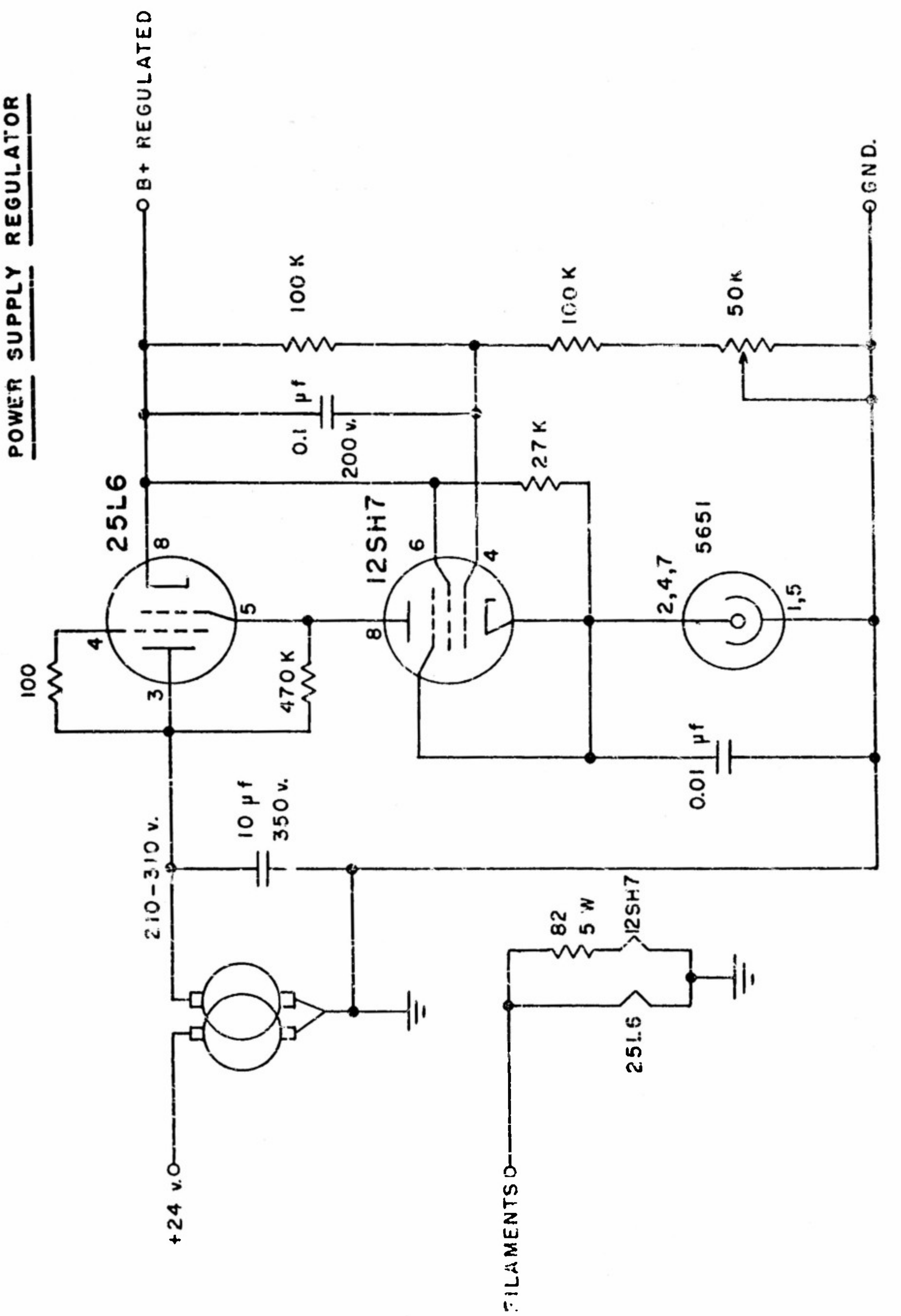
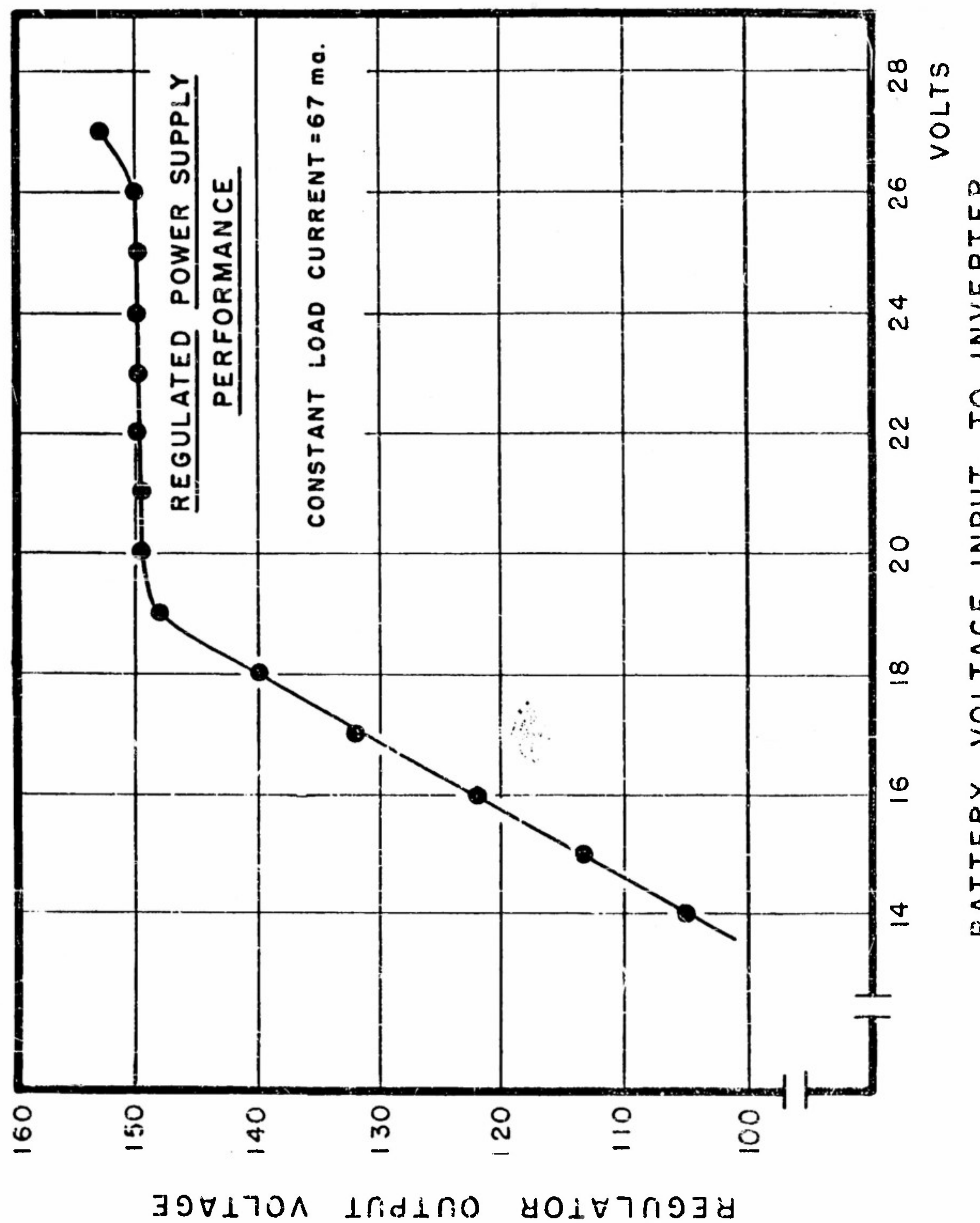

POWER SUPPLY REGULATOR
B+ REGULATED
GND.
100 K
100 K
50 K
0.1 μf
200 v.
27 K
25L6
8
5
4
3
100
470 K
12SH7
6
4
8
5651
2,4,7
1,5
0.01 μf
10 μf
350 v.
210-310 v.
+24 v.
82
5 W
12SH7
25L6
FILAMENTS

FIG. 20



REGULATED POWER SUPPLY
PERFORMANCE
CONSTANT LOAD CURRENT =67 ma.
160
150
140
130
120
110
100
REGULATOR OUTPUT VOLTAGE
14
16
18
20
22
24
26
28
VOLTS
BATTERY VOLTAGE INPUT TO INVERTER

Compass Repeater:

There is no nameplate information on the compass repeater, but it presumably was manufactured by the same company that manufactured the magnetic compass, namely, the General Electric Company. This unit has a small sealed synchro receiver that appears to be quite similar to the transmitter in the compass. It has higher impedance than does the transmitter, possibly because the transmitter was designed to drive two or more receivers. The thin needle on the face of the repeater is coupled to the synchro shaft. The wide needle is one that can be turned to any fixed position by means of the knob that extends out from the lower left-hand corner of the repeater face.

When received, the repeater had a four-pin Cannon connector at the rear of the case. This was removed in the interest of saving space. The leads to the synchro are brought out of the case to the terminal strip attached to the rear of the camera display panel.

A six-wire harness is the only connection between this camera display end of the recorder unit and the control panel end. Three of these wires are used for the above-discussed synchro leads, a fourth serves to energize the commutator indicator light, and the last two are for the indicating milliammeter.

Indicating Milliammeter:

This meter is designated as a Model 46-250, 3-1/2 inch, 250-degree milliammeter, with a full scale dial for one milliampere and an accuracy of one per cent of full scale. It was procured from the Hickok Electrical Instrument Company of Cleveland, Ohio. It was selected because of the fact that it has a long effective scale for its size. This is quite important in the application at hand in that a high degree of resolution of needle position is desirable since the meter is to be read from the film.

CONCLUSIONS

Throughout this report reference has been made to the versatility of the instrument. In any instrument of comparable complexity this versatility feature is a desirable one. It is believed that the instrument as it now stands is flexible, and it probably should remain so until it has been operated in the field. If use in the field should show that the operation is satisfactory in its present form, a series of changes could then be incorporated in a second design.

One of the more obvious of such changes would be in the W-Z relay system. Its function could easily be accomplished by a different arrangement of the cams on the secondary timer. However, these changes would be possible when writing the specifications for a new timer. Cutting of the cams is a critical job when it is necessary to have an accurate relationship between the different cams, and therefore it is a job that should be done by the manufacturer of the timers.

The control system in this instrument in its present form has the following control pulse requirements:

(1) A film exposure and film advance with the commutator unenergized.

(2) A film exposure and film advance sequence with the commutator and commutator indicator light energized.

(3) Either a repeat of (1) and (2), or a pulse to ready the instrument for a (1) operation at the beginning of the next readying cycle.

The above requirements are of course in addition to the switches S-2, S-3 and S-4 for controlling the filaments, B+ voltage, and the secondary timer.

If a new secondary timer were designed in as simple a form as possible, it might have two additional cams to accomplish this result. One of these would have two one-second closures at times 33 and 38 seconds to control the exposure of the film. The second cam would have two one-second closures at times 34 and 39 seconds to operate the film advance solenoid. The third would have a four-second closure starting at time 35 seconds to operate the commutator and the commutator indicator light. These three cams would replace the present S-1 arrangement on the secondary timer, and S-2, S-3 and S-4 would be retained in their present form for a total of six cams. The gain of this redesign, in addition to the simplicity, would be the elimination of the two relays, W and Z, and also the pulse delay relay.

It might be possible to eliminate the test relay and the test lights after some use of the instrument in the field. The indicator lights are not positive indication that the filaments are energized and that the B+ voltage is available since they light when voltage is applied to the filament bus and to the inverter bus. Another indication of satisfactory operation to a person preparing the instrument for a remote installation in water might be obtained by operating the test button with the test relay disconnected. The indicating milliammeter is visible to an operator with the recorder unit installed in the anchor unit shell. If the meter indicates satisfactorily, it is safe to conclude that the entire instrument is functioning normally. To do this, one must have the ultrasonic head immersed in water to close the acoustic circuit, but this can be done with the aid of a tank of water on the deck of the vessel.

Another possibility of improving this instrument is in the lead-acid battery unit. It could be that the latest nickel-cadmium batteries now available on the market might be more suited to this instrument application than the lead-acid type. The lead-acid types are somewhat limited in the number of charge-discharge cycles that can be executed without failure of the batteries. This is one of the advantages of nickel-cadmium types according to the manufacturers. It is quite possible that, due to the increased cost of these new types, they might be impractical to use because of the risk involved. However, a new design would warrant an investigation along these lines.

The limit on the film capacity for data that now exists on this instrument is due to the capacity of the camera driving spring. Some thought was given to the possibility of winding the spring using a motor driven by the battery. Taking two data exposures for each reading cycle, as the instrument is now arranged, there is no problem here. If it were desirable, for any reason, to extend the system to taking more than two exposures during each reading cycle, it would be necessary to look into this winding system, or to perhaps obtain a motor or solenoid-driven camera.

The primary timer is a very important consumer of battery energy even though its current demand is only 50 milliamperes. This amounts to the order of an ampere-hour per day just to keep the instrument going from one reading cycle to the next. This is a natural place to expend some effort for future instruments. It was not done for this experimental instrument because the objective was to build an instrument that could be used to evaluate the velocity detection scheme. There are several ways of reducing the amount of energy required for the operation of the primary timer that have been thought of in conjunction with this program. A spring-driven clock mechanism would be quite desirable for this purpose. The spring capacity should be adequate to drive the clock for at least eight days, and the minute hand of the clock should be made to make a contact twice in each revolution. The current rating of the contact would have to be large enough to carry a current to energize a relay. The dwell time of the contact should be something less than 59 seconds so that the secondary timer could interrupt its own circuit at time 59 seconds as it does in this instrument.

The clock could be employed to serve the function of the primary timer and also the function of the time-indicating clock in the camera display. It is believed that the indicating clock is a necessity even though the reading cycles are synchronized with the indicating clock because a failure of an intermittent character could occur, and the sequence of data on the film would be useless without the time being indicated.

A solenoid-wound, spring-driven clock would consume much less energy than the present primary timer, and could be employed as readily as the spring-driven clock.

A low-voltage protection system would be desirable in this instrument. If, for any reason, the instrument should fail in such a way that it made continuous reading cycles (this is not likely), or if the instrument could not be recovered on schedule, or if the terminal voltage of the batteries fell below a safe minimum, it would be advantageous to stop the instrument. The most simple approach to this problem would be to install a voltage-sensitive relay that would be energized by the primary timer contact before the secondary timer relay could be pulled up. The reading cycle would then be stopped, and the only thing that would continue to operate would be the primary timer. With the suggested spring-driven primary timer in use, the battery would be effectively disconnected from the instrument the first time this voltage-sensitive relay failed to operate.

MAINTENANCE INSTRUCTIONS

The battery unit should be fully charged before installation in the instrument so that a normal one-week operation will not drain an excessive amount of charge which would result in permanent damage to the battery. The manufacturer also recommends that it should not be left on the shelf for more than one month without being charged.

There has been some indication of relay contact failures after long periods of time when the instrument is not used. This is perhaps due to an oxidation of the contacts, and so it is recommended that before the instrument is operated after a long idle period the relay contacts should be lightly burnished to reduce this possibility of contact failure.

The tunable circuits should not require alignment very often, but it would be desirable to check the alignment whenever the opportunity presents itself. This operation requires that the ultrasonic head should be immersed in water, and the fish frame must be removed from the shell. The tuning requires only a short time, and the likelihood of the circuits getting detuned is slight so this is not a serious problem.

The full scale deflection of the one-milliampere indicating meter should be checked anytime the instrument is in such condition that it can be done. This can be accomplished without the acoustic path closed by water.

When the pushbutton on the phasemeter chassis is depressed while observing the indication on the milliammeter, a check can be made on the full-scale setting of the meter circuit. It should be set to one milliampere by means of the adjusting potentiometer also located on the phasemeter chassis. If, for some reason, it is not convenient to adjust the full-scale deflection, it should be read carefully and a note made of the reading. It can later be used to apply a correction factor to each reading on the film since a reading on this meter is important for its relationship to full scale rather than its relationship to one milliampere. In other words, whatever the full-scale current magnitude, it corresponds to 360 degrees of phase shift. To use the data with no correction factor requires that 360 degrees corresponds to exactly 1.0 milliampere.

All of the tubes are operated in the instrument in a conservative way. The matter of routine replacement will probably become apparent after some field use of the instrument. It should not be necessary to incorporate any periodic tube replacement schedule because the environment of the instrument is not one that is detrimental to tube life.

OPERATING INSTRUCTIONS

It is imperative that some form of check-off list be used when the instrument is located at some remote station in the water. There are many details which must not be overlooked, or the film will be blank when the instrument is recovered from the water. An operating procedure will be described which will prevent such occurrences.

(1) Install the battery unit in the anchor unit shell. Connect the battery cable to the battery unit. Put the shell cover in place on this end of

the tank.

(2) Install the recorder unit in the tank, leaving it extending somewhat from the end of the shell. Connect the main instrument cable to the water-tight connector on the recorder-end cover plate. Plug in the cable jumper provided from the cover-plate connector to the recorder-unit connector. (Note: This jumper is supplied simply to permit laying the shell cover on the deck while still permitting operation of the instrument.)

(3) The fish shell should now be assembled as far as installing the ultrasonic head, the tail fairing, and the tail fins.

(4) Make the connections on the fish frame unit: (a) the two BNC connectors on the coaxial jumpers to the coaxial switch, (b) plug in the compass and the coaxial switch Cannon connectors, and (c) plug in the Jones connector.

(5) With the fish shell in an upright position, install the fish frame unit, compass-end first, into the front end of the fish shell. The compass should be right-side-up, and the phasemeter chassis upside down.

(6) Plug in the two BNC connectors from the ultrasonic head into the alternate mating connectors on the coaxial switch. Plug the shell Jones connector into its mate on the fish frame.

(7) Install the nose and plug the main cable from the anchor unit into the water-tight connector on the fish shell.

At this point the instrument is ready for operation and checkout which should proceed as follows:

(1) Plug in the connector on the end of the small cable from back in the recorder-end compartment that comes from the battery unit bulkhead.

(2) Put the main start toggle switch (located on the far left-hand side of the control panel) in the "on" position. The primary timer should start to run.

(3) Push the "test" button (located at the top center of the control panel), and a reading cycle should commence. The pushbutton must be held for approximately one second while the secondary timer advances to the time "zero" position, at which time the S-4 shunt-down pulse is removed from the timer relay, and it can then hold itself up. Immediately the filament light should go on and the timers are both running. After about one-half minute, several things should occur simultaneously. The dynamotor and the 400-cps. inverter should start, the "B+" light should come on, and the coaxial switch in the fish will either advance or not, and a deflection should occur in the milliammeter. A few seconds later the film solenoid will advance the film, and an exposure will be taken as the camera light comes on. The indication of the meter when the light comes on is the important one. Other operations will occur for several seconds which are not too important for the present purpose of checking out the instrument. Then the camera light will come on for a second time and stay lighted for about a second. This second indication, regardless of where it is on the meter dial, should be similar to the first indication. If the first indication was near zero or near full scale, then the second one might be the opposite. This is because of the inherent slight phase difference between the upstream and the downstream position of the coaxial switch.

This difference is small and constant, and if the fish is situated in a tank of still water there will be no water-velocity-induced phase shift. If the fish is suspended over the side of the vessel in the water, and if the vessel is moving, this difference in meter reading will increase as the velocity of the vessel is increased. This last operation described is not a necessary one for checking out the instrument because obtaining a pair of readings with the fish situated in a tank of still water is a sufficient test when the readings come out to be quite close together.

After the operation of the instrument has been demonstrated by the above test procedure, it is necessary to go through the checkout procedure before closing up the instrument prior to submerging it.

The following will accomplish the checkout:

(1) Put a new magazine in the camera.

(2) Wind the camera spring as far as it will go.

(3) Push the camera light "test" button.

(4) Check that the main start toggle switch is in the "on" position (up), and that the primary timer is running.

(5) Remove the cable jumper from the shell cover to the control panel and plug the cover connector into the mate on the control unit.

(6) Put the recorder end shell cover plate in place.

The instrument is now in automatic operation, and can be lowered to its position on the bottom of the bay or estuary.

APPENDIX A

DRAG-DISC METER

The Drag-Disc and Associated Transducers:

The experimental determination of the velocity of estuarine waters by the measurement of the drag force on a solid body submerged in the flow is made attractive by the simplicity and directness of the method. A system employing this principle was considered in some detail. A flat circular disc was chosen for the drag element. The advantages of using a flat disc are several: (1) The surface drag on a disc normal to the velocity is negligible compared to the form drag, and the line of separation of flow is well defined at the rim of the disc -- the drag coefficient is therefore independent of the surface roughness (which may change with time). (2) The drag is only slightly changed due to small deviations of the normal of the surface to the direction of flow -- it is estimated that, when the deviation is 10 degrees, the drag is changed by only one per cent. (3) Another advantage, though not a necessary one, is that the drag coefficient for a disc is constant for Reynolds number larger than 10^3.

It was proposed to attach the disc to the free end of a cantilever beam, and to determine the drag by measuring the inclination of the disc or the strain in the cantilever. No completely satisfactory technique has been found for measuring the inclination of the two ends of the cantilever, however. The Y-type Position Convectron was suggested. A pair was obtained from the Red Bank Division of the Bendix Aviation Corporation. Tests indicated that the reproducibility of the Convectron output at a given inclination was very poor. These tests were described in Appendix I of the "Progress Report for the Period Ending 15 June 1953".

Resistance strain gauges were considered for measuring the strain produced in the cantilever by the drag force on the disc. Gauges were applied to a test cantilever, and the gauge terminals were connected to a self-balancing bridge employing a servo-amplifier. Suitable sensitivity and stability were obtained from this apparatus while investigations were being made of the relationship of water velocity to cantilever strain. The study revealed that the velocity range of 0.08 to 5.1 feet per second corresponds to a cantilever strain range of 400:1.

The size of the disc and the dimensions of the cantilever must be such that the strain produced at the lowest velocity to be measured can be observed with the desired accuracy. For the requirements of this project a disc 8.5 inches in diameter and a cantilever 2 feet long with 3/8 inch by 1/16 inch cross-section are required. With this arrangement, the strain produced at the fixed end of the cantilever by a current of 0.1 foot per second is about 30 times 10^{-6} inch -- which can be measured with reasonable accuracy by means of resistance gauges. A smaller and sturdier arrangement, though structurally more desirable, will not produce large enough strain to be measured satisfactorily. If the requirements are relaxed as to the accuracy of measurements and the lower limit of velocity to be measured, a sturdier cantilever and a smaller disc may be used. However, such less severe requirements may be satisfied with ordinary current meters.

In addition to the requirement that the cantilever must be slender enough to give measurable strain with the lowest velocity to be measured, the beam must, on the other hand, be strong enough to withstand the force due to higher velocities. Since the size of the cantilever is already determined to satisfy the former requirement, resistant force must be applied behind the disc to bring the strain produced by the highest velocity that may be encountered within allowable limits. A nonlinear helical spring with resistance proportional to the third power of its deformation is found to be suitable for this purpose. However, to satisfy the requirements of this project in a practical form is impossible to manufacture. Should the magnitude of the lowest velocity to be measured be sufficiently increased, such a spring may become a possibility. For the present project, three cantilevers were suggested offering resistance closely similar to that of a cubic spring. With this arrangement, the maximum displacement of the disc is 6 inches under a velocity of 5 feet per second. Barring disturbances due to turbulence in the flow and movement of the support, the error of observation due to an error in strain measurement of 10^{-6} inch is considerably less than 0.006 foot per second for velocities up to one foot per second, and is less than 0.012 foot per second for velocities from one foot per second to 5 feet per second.

The Stable Float Tank (Meter Housing):

The ultrasonic meter may be mounted in a conventional housing and supported from above. Although the meter may be given some vertical motion due to the movement of the body from which the meter is suspended, this vertical movement does not affect appreciably the measurements.

The drag-disc measurements, on the other hand, are extremely sensitive to any vertical motion of the meter. It is estimated that if the vertical velocity of the support is equal to one-half the horizontal velocity being measured, the drag force is increased by nearly 20 per cent, and if the vertical velocity is equal to the horizontal velocity, the error is about 60 to 70 per cent. Thus, for the accuracy specified for the lowest velocity to be measured in this project, the meter must be so positioned that its vertical velocity due to disturbances will be less than the lowest velocity to be measured. For this reason, the support for the drag-disc meter cannot be suspended from such floating bodies as boats or buoys which are subjected to the action of surface waves. It is suggested that the drag-disc meter should be attached to a stable float tank which, together with measuring and recording instruments housed inside, has an overall density less than water, and can therefore be anchored by means of a cable to the bottom of the estuary. With this arrangement, the position of the meter is free from disturbances due to surface waves. Of course, if the requirements as to the lowest velocity to be measured and the accuracy of measurements are relaxed to a large enough extent, a conventional housing suspended from a buoy or boat may be used even with the drag-disc meter. However, under such conditions the drag-disc is not necessary since an ordinary current meter may be adequate.

The meter is to be used for measuring continuously the velocity of flow at a point in the estuary, and therefore the position of the meter should not change during the period of measurement. Since such a fixed position is impossible to maintain unless the instrument is mounted on a rigid footing, some drift of the meter vertically and horizontally must be tolerated with both the suspended and the anchored instruments. The drift increases with the length of the cable and with the drag on the cable and the meter-float assembly; and decreases with an increase of the net vertical force acting on the buoyant housing. For this project the allowable drift at maximum velocity is 100 yards horizontally and two feet vertically. This requires a 10 to 1 ratio of the vertical force to the horizontal force acting on the meter-float assembly at the highest velocity of 5 feet per second. When a suspended housing of conventional design is used, this condition can be attained simply by increasing the weight of the meter and housing. On the other hand, with the buoyant housing anchored to the bottom of the estuary, the upward vertical force can be increased only by increasing the volume of the float tank. Using a buoyant force to drag force ratio of 10 to 1, an attempt was made to design a stable float tank 12 inches in diameter and 72 inches long. Both of these dimensions were larger than desired, but this method of positioning seemed to offer maximum flexibility to applications in estuarine research. Of the many suggestions considered, only one type of design (within the limits of time and money available) seemed capable of withstanding the buckling forces at or near the maximum operating depth of 180-200 feet. This design required a one-half inch thick wood shell. The practical aspects of building a water-tight shell with a thin glued-up wall were discussed with Dr. Pritchard. The conclusion of this discussion was that in view of the hazards of obtaining water-tightness with this type of construction and the undesirable size, it seemed wise to abandon this method of positioning.

It should be remembered that the relatively large dimensions of the above float tank were dictated by the sensitivity of the drag-disc meter to vertical motion, the extremes of velocities to be measured, the required accuracy of measurements and the limited allowable drift of the meter. If these requirements are relaxed, a smaller shell may be used.

It should be mentioned that an attempt was made to use a paravane for the support of the drag-disc meter with the idea that its size could be smaller for the same net vertical force. This idea does not work because, due to the finite length of the paravane, the induced drag is quite large. To maintain the 10 to 1 ratio of vertical buoyant force to horizontal drag force the required size of the paravane is even larger than the shell described above.